Technical Report

UDC 629 . 11 . 012 . 5 : 669 . 14 . 018 . 295 . 2

Wire Rod for High Tensile Strength Steel Cords

Masashi SAKAMOTO* Toshihiko TESHIMA
Kenichi NAKAMURA

Abstract

To achieve the weight reduction of automobiles and fuel consumption improvement, wire rods for high tensile strength steel cords have been developed. However, the problem of developing high tensile strength steel cords is that both high tensile strength and excellent ductility must be obtained simultaneously. In order to resolve this problem, the mechanism of cracking during wire drawing and the improvement of drawn wire ductility were investigated by analyzing the change in the microstructure and mechanical properties of the drawn wire with wire drawing. By applying 1.0%C hypereutectoid steel and the optimized drawing technique, 4 400 MPa grade steel cords could be obtained in the laboratory. This paper describes these research topics and the developed steel for high tensile strength steel cords.

1. Introduction

Steel cords are a high tensile strength steel material used for rubber products such as tires and hoses as a reinforcing material. **Figure 1** shows the schema of the structure of a radial tire. Steel cords are mainly used for the belt and carcass part of the tire. Their annual consumption has reached more than 2 million tons in the world.

As the primary property of steel cords, they require a tensile strength that is high enough for use as a reinforcing material. **Figure 2** shows the trend of the tensile strength of steel cords.[1] The tensile strength was about 2 800 MPa in the 1970s, which increased year by year, and 4 000 MPa high tensile strength steel cords were developed in the mid-1990s. The tensile strength is highest among those of commercially available steel products. However, the demand for fuel consumption improvement and higher loading capacity continues to remain strong. Therefore, the steel cords require the higher tensile strength to satisfy such requirements of lighter tires, lower rolling resistance and higher resistance to ever growing load. On the other hand, the drawability and the ductility of wires deteriorate as the wire tensile strength increases. The suppression of such ductility deterioration is required when considering the further enhancement of the tensile strength of steel cords.

To achieve higher tensile strength of steel cords, this paper examines the methods required to enhance the tensile strength of steel cords and the behaviors of the transitions of the mechanical properties and the microstructures in wire-drawing, and introduces the high tensile strength steel cords developed based on a hypereutectoid steel.

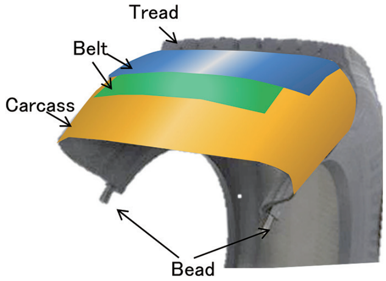


Fig. 1 Structure of radial tire

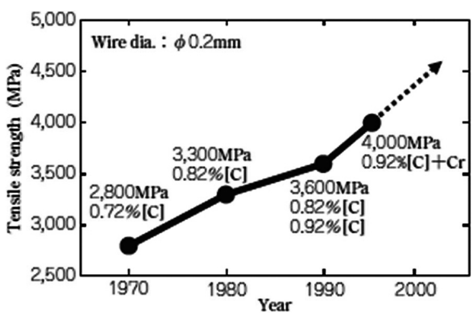


Fig. 2 Trend of high tensile strength of steel cords[1]

* Researcher, Bar & Wire Rod Research Lab., Steel Research Laboratories
23-15 Suzuko-cho, Kamaishi City, Iwate Pref. 026-8567

2. Considerations when Developing High Tensile Strength Steel Cords

2.1 Properties required of high tensile strength steel cord steel

Steel cords are manufactured by drawing a high carbon steel wire rod to a fine diameter wire, patenting, drawing the wire to a high tensile strength ultrafine wire of 0.15–0.39 mm in diameter, and then twisting and stranding the wires into cords (**Fig. 3**). The tensile strength is the primary property required of steel cords. There are three major methods of obtaining the high tensile strength of a high carbon steel wire. They are: (1) imparting high tensile strength to patented wires before drawing, (2) increasing the amount of reduction in the drawing process, and (3) strengthening work-hardening in the wire drawing. By combining these strengthening mechanisms appropriately, it is possible to obtain high tensile strength wires. Furthermore, the high tensile strength of a steel wire is achieved by increasing the carbon content and by adding Cr as shown by the chemical compositions in Fig. 2.

Among these strengthening mechanisms, the work hardening in the wire-drawing is crucial for achieving the high tensile strength of ultrafine steel wires such as steel cords. The tensile strength of ultrafine high tensile strength steel wire is obtained by the work hardening developed by the heavy work conducted in the final wire-drawing process (wet drawing), which can attain a level of 97% or higher in terms of the total area reduction. This work hardening is large enough to apportion 65% of the entire tensile strength.[2] In other words, in order to achieve the high tensile strength of steel cords, the work hardening developed by the heavy wire drawing work is indispensable. Furthermore, in the final twisting and stranding process after the wet drawing, large twisting and bending stresses act on the wire. Additionally, in the first dry drawing, high drawability is required of the wire so as to ensure the drawing of the fine diameter wire required for patenting. Therefore, the ductility to withstand such manufacturing processes is essentially required of the steel cord steel. The indices of such ductility are: the reduction of area in the tensile test and the generation of longitudinal cracks (delamination) in a torsion test.

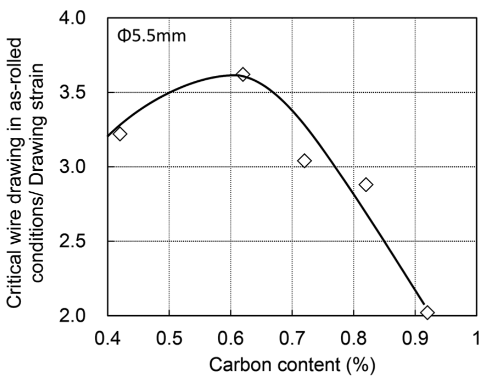


Fig. 4 Relationship between critical wire drawing and carbon content[3]

2.2 Relationship between carbon content and ductility of high tensile strength steel wire

Figure 4 shows the relationship between the carbon content and the drawability,[3] wherein the drawability is judged based on the reduction of area in the tensile test (to be equal to or higher than 35%) and the number of torsional revolutions reached at fracture (to be higher than 25) in a wire torsion test. Along with the increase of the carbon content, the drawability deteriorates, which means that the drawability deteriorates to a lower value. When the drawability deteriorates, the drawing of the wire in the dry drawing to the required diameter wire is impossible. Therefore, an intermittent patenting treatment is required, and deterioration in productivity is thus developed. In addition, due to the insufficient amount of the drawing strain in the wet drawing, a deficit in the tensile strength of the high tensile strength steel wire and/or the fracture of the wire in the twisting process become issues of concern.

2.3 Relationship between wire diameter and ductility of high tensile strength steel wire

The ductility of the high tensile strength steel wire also depends on the diameter of the steel wire. **Figure 5** shows the behaviors of the transitions of the tensile strength and the reduction of area when wires of various diameters are drawn.[4] As the wire diameter becomes smaller, the drawing strain at which point the reduction of area starts to deteriorate rises. The generation of delamination in a torsion test also exhibits a similar trend, and it is reported that as the initial wire diameter becomes larger, the delamination is generated at a smaller drawing strain.[5] This is what is termed as the size effect. Although its mechanism has not yet been clarified, low strain aging in the fine diameter wire is proposed as one of the effects.[6] The strain aging is reduced in fine diameter wires because the differ-

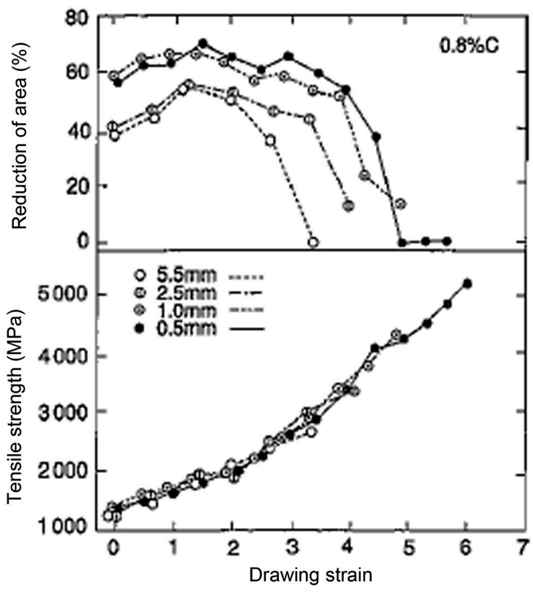


Fig. 5 Effect of wire diameter on mechanical property with drawing strain[4]

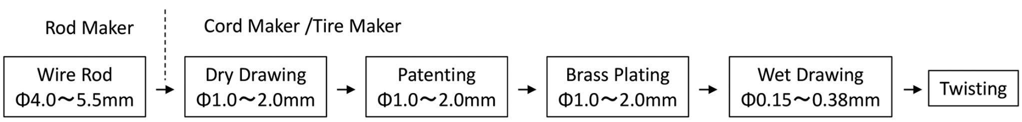


Fig. 3 Manufacturing processes of steel cords

ence between the microstructure of the subsurface layer and that of the center area is small in fine diameter wires,[3] and the processing-induced heat generation amount and the heat releasing rate differ due to the difference of the wire-drawing processes (wet drawing is applied to drawing the fine diameter wires and dry drawing is applied to drawing thick diameter wires). This means that in the manufacturing of steel cords, the behaviors of ductility deterioration and microstructure transition during wire drawing are different in the dry drawing and the wet drying. Accordingly, in order to achieve the high tensile strength of steel cords, it is important to clarify the behaviors of the transitions of the mechanical properties and the microstructures in the dry drawing (first wire drawing) and the wet drawing (finishing wire drawing), and to enhance ductility in the respective drawing process.

3. Behaviors of Transition of Mechanical Properties and Microstructure during Wire Drawing

3.1 Microstructure factor and mechanical properties of pearlite steel

The steel material used for the steel cords is a high carbon steel with a pearlite microstructure. As shown in **Fig. 6**, the pearlite steel has the microstructure of stratified hard cementite layers and soft ferrite layers, and is composed of pearlite blocks wherein the ferrite crystal orientations are identical. A pearlite block is composed of pearlite colonies wherein the directions of the cementite layers are identical. The spacing in between each cementite layer is termed as lamellar spacing. In the relationship between the microstructure and the mechanical properties, it is considered that the lamellar spacing affects the tensile strength[5], and the pearlite block size (hereinafter referred to as PBS) is considered to affect the ductility (reduction of area)[7].

3.2 Enhancing ductility in dry wire drawing

3.2.1 Relationship between mechanical properties and microstructure factor of dry-drawn wire[8]

Figures 7 and **8** show the effects of PBS and the lamellar spacing on the tensile strength and the reduction of area in dry wire drawing. The test sample was a 5.5 mm in diameter SWRH82A wire rod and PBS and the lamellar spacing were controlled by lead patenting.

Above a PBS of 35 μm, the behavior of the transition of the mechanical properties of the drawn wire differs significantly. In the area above the drawing strain (true strain) 1.0–1.2, the reduction of area deteriorates rapidly to almost 10%, and the work-hardening percentage also deteriorates. Thereafter, the reduction of area exhibits low values, and above the drawing strain (true strain) 2.0, the tensile strength also deteriorates. Furthermore, this trend is more remarkable as PBS is coarsened. Below a PBS of 30 μm, although the effect of PBS on the tensile strength is small, the deterioration of the reduction of area in the vicinity of drawing strain (true strain) 3.0 is relieved slightly by refining PBS.

Regarding the effect of the lamellar spacing on the mechanical properties of the drawn wire, up to the drawing strain (true strain) 3.0, the tensile strength continues to rise with almost the same work hardening percentage at all levels, and starts to deteriorate at the drawing strain (true strain) 3.0. The reduction of area deteriorates rapidly above the drawing strain (true strain) 2.5, and along with the refining of the lamellar spacing (tensile strength rises), the drawing strain (true strain) at which point the reduction of area starts to deteriorate reduces.

Based on these findings, in order to secure the ductility (reduction of area) of the drawn wire of the pearlite steel, a PBS of less than 30 μm and the coarsened lamellar spacing (tensile strength deteriorates) are considered effective.

3.2.2 Analysis of mechanism of ductility deterioration in early stage of wire drawing

As Fig. 7 shows, above a PBS of 35 μm, the reduction of area deteriorates rapidly in the early stage of the wire drawing. This is attributed to the cracks that are generated in the early stage of the wire drawing and grow subsequently. **Figure 9** shows the result of the macroscopic observation of the longitudinal section in the center area of the drawn wire.[8] Above a PBS of 35 μm, a crack is generat-

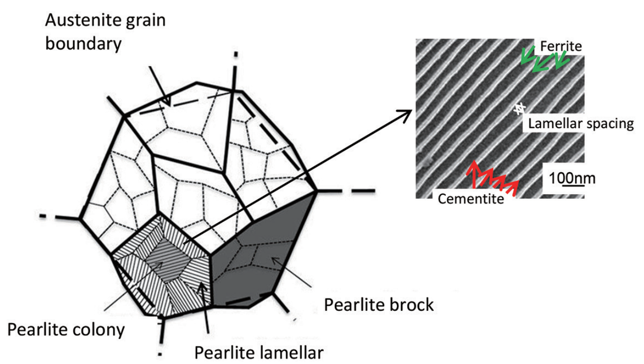
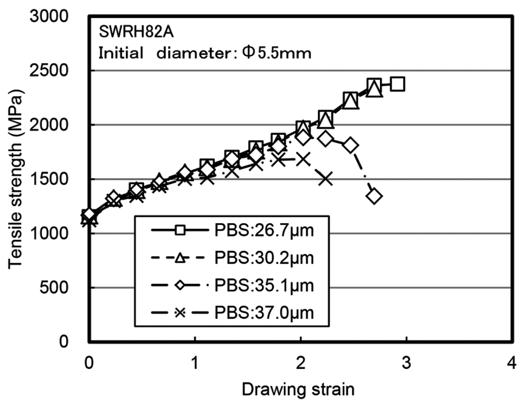
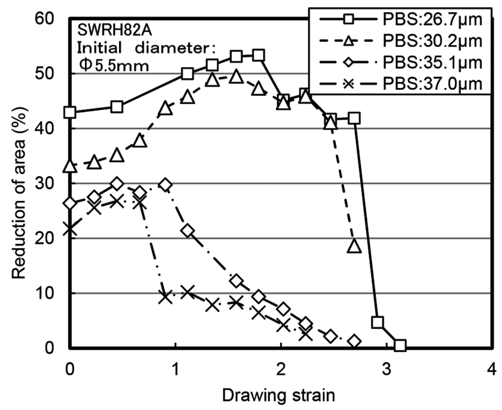


Fig. 6 Structure of perlite steel

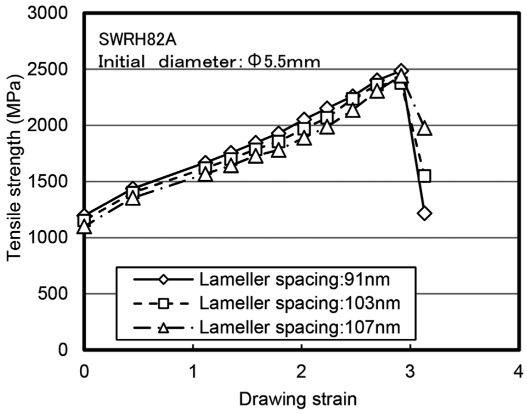


(a) TS: Tensile strength

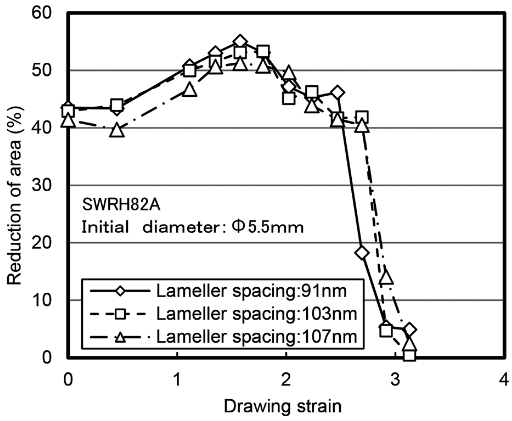


(b) RA: Reduction of area

Fig. 7 Effect of PBS on mechanical property with drawing strain (dry drawing)[8]



(a) TS: Tensile strength



(b) RA: Reduction of area

Fig. 8 Effect of lamellar spacing on mechanical property with drawing strain (dry drawing)[8)]

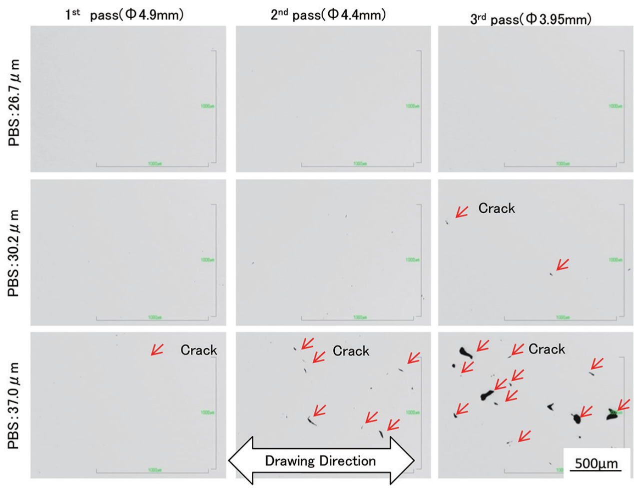


Fig. 9 Generation and growth of crack in center area[8)]

ed in the center area in the first pass (area reduction is 17%), and grows subsequently. **Figure 10** shows the result of the observation of the vicinity of a crack by a scanning electron microscope (SEM). The crack is generated in the shearing direction of 45° with respect to the drawing direction, and propagates. Furthermore, in the neighborhood of the crack, a phase in which the lamellar microstructure

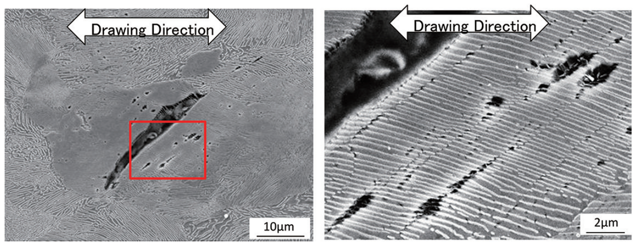


Fig. 10 SEM images showing crack

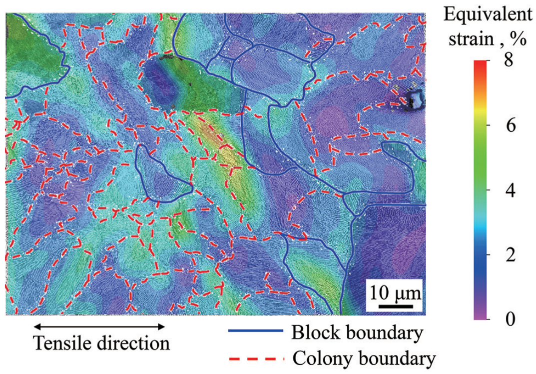


Fig. 11 Local strain distribution map of perlite[9)]

appears to have moved in the same direction is observed in the same block. In the peripheral microstructure, cracks and the moved lamellar microstructure are also observed. However, they are not formed uniformly, and a phase in which they are formed concentratedly in a particular region is confirmed. A more in-depth analysis of the mechanism of the generation of such cracks and the movement of the lamellar microstructure was thus conducted.

3.2.3 Generation and growth mechanism of crack in pearlite steel[9)]

During the drawing of a wire, the shearing stress acts in the subsurface layer and the tensional stress acts in the center area. Therefore, to analyze the mechanism of the generation of cracks in the center area, the analysis was conducted with respect to the state of the local plastic deformation and the change of the microstructure when a tensile stress is applied.

The distribution of the local strain when a tensile stress is applied was observed by the digital image correlation analysis (DIC). As **Fig. 11** shows, the local strain is non-uniformly distributed. Furthermore, the value of the local strain varies even in an identical block, and the plastic deformation depends on the colony.

The change of the value of the local strain is affected by the relationship between the direction of the tension and the ferrite slip systems (Schmid factor) and the angle between the tensile direction and the lamellar alignment angle. As **Fig. 12** shows, as the Schmid factor rises, the value of the local strain along the tensile direction tends to increase, and the local strain distribution is affected by the extent of the activity of the ferrite slip systems. Furthermore, even when the Schmid factor is high, the value of the local strain along the tensile direction varies depending on the relationship between the lamellar cementite alignment angle and the tensile direction (**Fig. 13**). It is confirmed that in the case of the angle between the lamellar cementite alignment angle and the tensile direction being 0° or 90°, the value of the local strain along the tensile direction is small, and is large in the case of the angle being 45°.

Based on these findings, the plastic deformation under the ten-

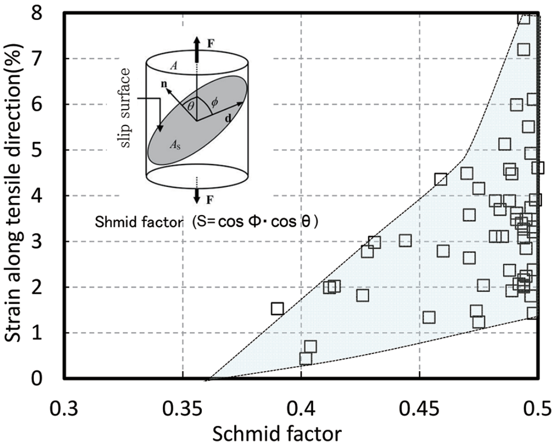


Fig. 12 Relationship between the Schmid factor and local strain[9]

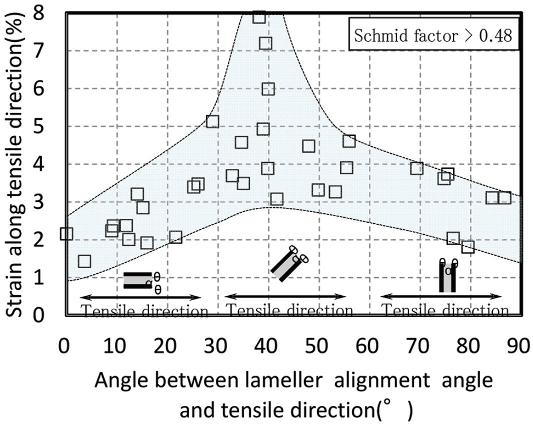


Fig. 13 Relationship between lamellar alignment and local strain[9]

sile stress in pearlite steel was studied. In the case of the high Schmid factor and the angle between the lamellar alignment angle and the tensile direction being 45°, the movement of the dislocation is not restricted. Therefore, the value of the plastic deformation becomes large, and the deformation and/or the rotation of the crystal of the cementite and/or the ferrite occur. On the other hand, in the case of the high Schmid factor and the angle between the lamellar alignment angle and the tensile direction being 0° or 90°, the dislocation formed in the ferrite is restrained at the cementite boundary, and the plastic deformation does not develop. Accordingly, the crystal rotation of the cementite and/or the ferrite does not occur. The movement of the lamellar microstructure in the sharing direction and the generation of cracks are considered to be developed in the following manner. When a tensile stress is applied further, the accumulation of the dislocation at the cementite boundary increases. In the case that the tensile direction and the lamellar cementite alignment are parallel, the cementite is subject to higher tensile stress, and being combined with the accumulated dislocation, the cementite is fractured on the slip line and combined again. It is considered that a similar phenomenon occurs in the center area during the wire drawing, and cracks are generated thereby.

Furthermore, the effect of PBS on the value of the local strain along the tensile direction is shown in **Fig. 14**. With the coarsened PBS, the value of the local strain along the tensile direction increases at the lamellar alignment of 45°. However, with the fine PBS, the value of the local strain is small and scatters less. This means that,

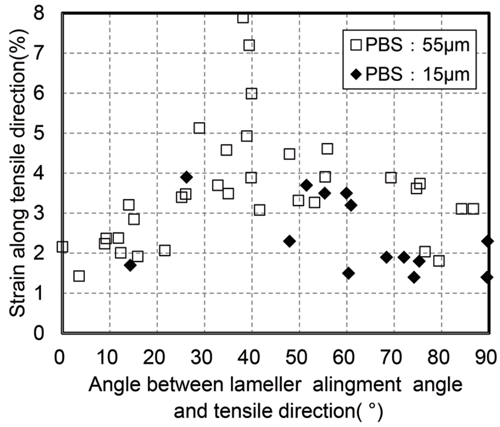


Fig. 14 Relationship among lamellar alignment, local strain and PBS

with the coarsened PBS, the non-uniformity in the local strain distribution increases. Due to the increase of the non-uniformity of the local strain, the non-uniformity of the local tensile stress also increases, and the aforementioned mechanism is encouraged, and cracks are considered to be generated in the coarse PBS.

3.3 Enhancing ductility in wet wire drawing

3.3.1 Factors deteriorating ductility of high tensile strength steel wire

The deterioration of the ductility of the high tensile strength steel wires is represented by the deterioration of the reduction of area and/or the longitudinal crack (delamination) developed in twisting. One of the factors that deteriorates the ductility is the local strain aging embrittlement caused by the lamellar cementite decomposition.[6]

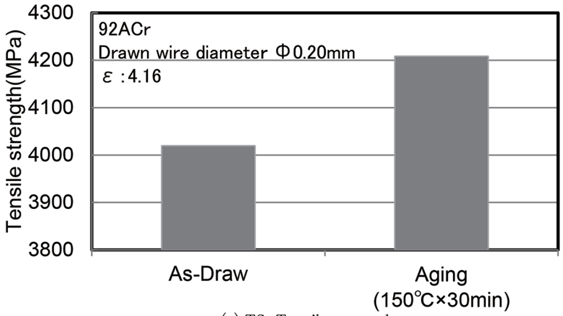
Figure 15 shows the change of the mechanical properties of the wet-drawn and aging-treated SWRS92A ultrafine high tensile strength steel wire 0.2 mm in diameter (drawing strain ε: 4.16). By applying the aging treatment at 150°C, the tensile strength increases. However, the reduction of area deteriorates and, regarding the torsional property, the twist value (total number of torsion reached at the fracture) also deteriorates due to the generation of delamination.

Takahashi et al. report as follows about the change of the microstructure due to the aging treatment.[10] As a result of the analysis of the state of the distribution of the carbon element with the 3-dimensional atom probe (3D-AP), the carbon elements are maintained in the lamellar state in the as-drawn wire. However, the cementite is decomposed by the aging treatment at 150°C, and the carbon elements are dispersed uniformly in the ferrite. The change of the mechanical properties as shown in Fig. 15 is also considered to be developed similarly by the cementite decomposition.

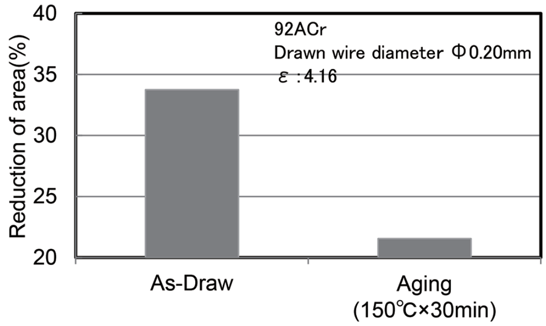
3.3.2 Method of enhancing ductility of high tensile strength steel wire

It is proposed that the strain aging is the mechanism of the cementite decomposition developed by the transfer and the adhesion of carbon to the dislocation in the ferrite due to the high affinity of carbon for the dislocation.[6] Assuming that the local cementite decomposition develops the segregation of the carbon in the dislocation, the reduction of the dislocation (drawing strain) and/or the reduction of the processing-induced heat generation are considered effective as the suppressing measures.

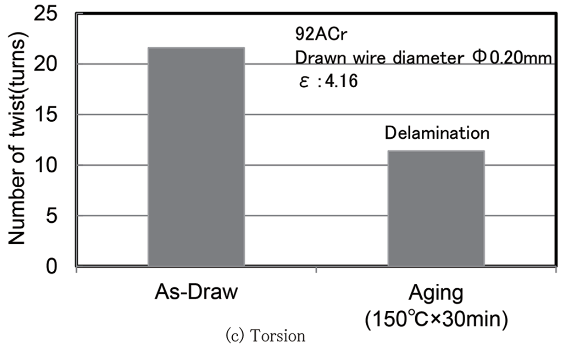
To reduce the value of the drawing strain, the increase of the tensile strength of the patented wire and increasing the amount of work hardening are effective. Tarui, et al. report that to enhance the tensile



(a) TS: Tensile strength



(b) RA: Reduction of Area



(c) Torsion

Fig. 15 Relationship between mechanical property and aging

strength of the patented wire and to increase the amount of work hardening, C and/or Cr are effective (**Fig. 16**, **Fig. 17**)[11]. On the other hand, careful attention is required because as the carbon content rises, the drawability deteriorates, and the proeutectoid cementite is formed.

Regarding the reduction of the processing-induced heat, Tashiro, et al. studied the countermeasures in the secondary processing with respect to die design, lubrication film, pass schedule, back tension and the like, and report that the ductility is improved by enhancing the lubricant performance and by the low die approach angle.[4]

However, if the cementite decomposition is suppressed excessively, the tensile strength deteriorates. **Figure 18** shows the relationship between the wire-drawing speed and the mechanical properties of the drawn wire. As the wire-drawing speed is lowered, the reduction of area is improved, the delamination is suppressed, and the ductility is improved thereby. However, below the drawing speed of 100 m/min, the ductility is not improved, and the tensile strength deteriorates. The change of the mechanical properties is considered due to the change of the states of the cementite decomposition caused by the change of the processing-induced heat and the dynamic strain aging when the wire drawing speed is changed. Therefore, from the result, the cementite decomposition does not

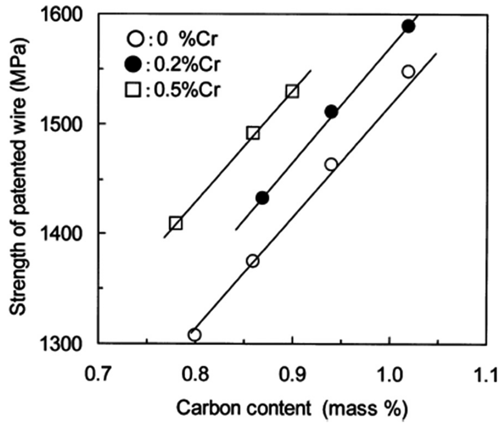


Fig. 16 Effect of C and Cr content on patented wire strength[11]

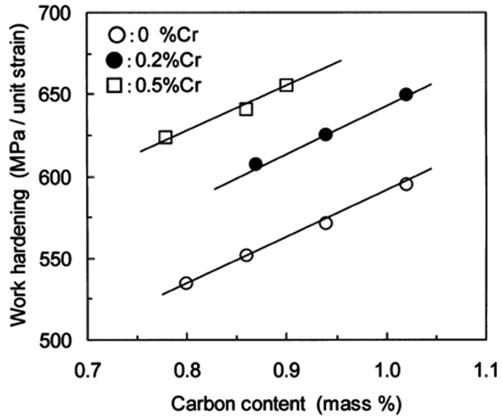


Fig. 17 Effect of C and Cr content on amount of work hardening[11]

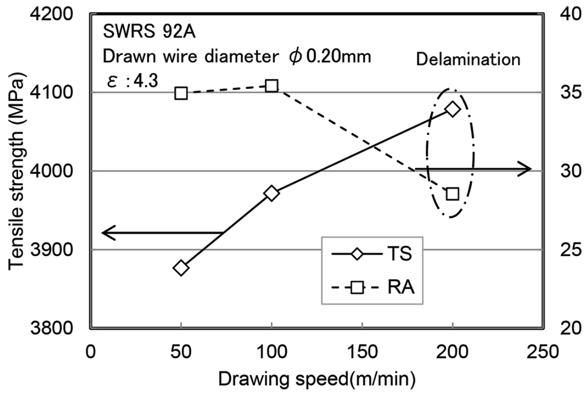


Fig. 18 Relationship between drawing speed and mechanical property of drawn wire

need to be suppressed in any way, and an optimized condition is considered to exist. Tarui, et al. assume that the delamination is generated when the cementite decomposition progresses and the carbon content in the ferrite exceeds 1% (**Fig. 19**)[12].

As stated so far, in order to obtain the high tensile strength steel wire excellent in both tensile strength and ductility, it is important to control the cementite decomposition to within a certain appropriate range by optimizing the wire drawing condition. However, as the tensile strength of the steel wire is enhanced, the processing-induced heat during the wire drawing also rises, and the strain aging pro-

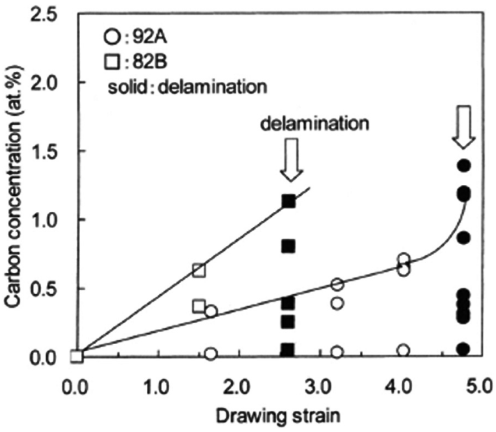


Fig. 19 Relationship between carbon concentration in ferrite with drawing strain and occurrence of delamination[12)]

gresses more readily. Therefore, there should be a different optimized secondary processing technique depending on the type of steel materials. Namely, in order to enhance the tensile strength of steel cords, not only the development of the steel material, but also the development of the secondary processing techniques is crucial as well.

4. Development of High Tensile Strength Steel Cords Based on Hypereutectoid Steel

Development of a hypereutectoid steel with a carbon content above 0.90% as shown in **Table 1** is in progress for high tensile strength steel cords. The trial processing of the high tensile strength steel wire was conducted by combining the hypereutectoid steel with the secondary wire processing techniques. **Figure 20** shows the relationship between the tensile strength and the drawing strain of various types of steel. The diameters of the patented wires were determined so as to commonly obtain the same final finish wire diameters of 0.2 mm for all high tensile strength steel wires even when the drawing strain was changed. In any type of steel, the high tensile strength steel wire excellent in ductility with a tensile strength exceeding 4000 MPa was obtained without delamination. Although the drawing strain at which the delamination is generated lowers when C content is increased and Cr is added, the tensile strength level at which the delamination is generated rises, and the balance between the tensile strength and the ductility could be improved. As a result thereof, although based on laboratory conditions, by using 102C+Cr steel, the high tensile strength steel wire with a tensile strength of 4400 MPa was obtained without the generation of delamination.

5. Conclusion

This study introduced the behaviors of the transitions of the mechanical properties, and the improvement of the ductility of the high tensile strength steel wire based on the detailed analysis of the mechanical properties and the microstructures during wire drawing. The high tensile strength steel cord steel based on a hypereutectoid steel is also described. As a result thereof, by using the hypereutectoid steel with C content exceeding 1.0% and by optimizing the secondary processing technique, although based on laboratory conditions, the high tensile strength steel wire of 4400 MPa could be developed without the generation of delamination. However, the mechanism of the deterioration of the ductility such as the one due to delamination has not yet been clarified. Therefore, in order to obtain higher tensile strength, the clarification of the mechanism of the ductility deterioration and the establishment of the techniques that suppress the ductility deterioration are crucial. In recent years, great progress has been made in the analysis techniques, and the analysis of the microstructures and the observation of the changes thereof on the nanometer basis have become realized. Hereafter, we are determined to conduct studies to clarify the ductility deterioration mechanism by fully taking advantage of these analysis techniques, and to make efforts to further enhance the current high function of steel cords such as high tensile strength and high ductility.

Table 1 Chemical compositions of developed steel for high tensile steel cords

(wt.%)

Steel	C	Si	Mn	Cr
102C+Cr	1.02	0.20	0.30	0.20
97C+Cr	0.97	0.20	0.30	0.20
92C+Cr	0.92	0.20	0.30	0.20
92C	0.92	0.20	0.50	–

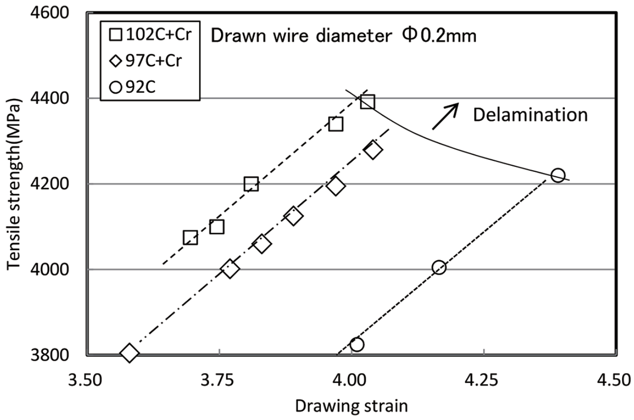


Fig. 20 Trial results of developed steel for high tensile steel cords

References

1) Oki, Y.: Bull. Iron Steel Inst. Jpn. 8 (9), 627–632 (2003)
2) Tashiro, H., Nishida, S., Tarui, T., Oohashi, S., Sasaki, S., Nakamura, K., Yoshie, A., Demachi, H.: Shinnittetsu Giho. (370), 39–44 (1999)
3) Funayama, T.: Shinnittetsu Sumikin Giho. (406), 43–46 (2016)
4) Tashiro, H., Tarui, T.: Shinnittetsu Giho. (378), 77–80 (2003)
5) The Japan Society for Technology of Plasticity: Technology of Plasticity Series 6 Drawing Processing. Corona Publishing Co.,Ltd., 1990, 272p
6) Tarui, T., Maruyama, N., Tashiro, H.: Tetsu-to-Hagané. 91 (2), 265–271 (2005)
7) Takahashi, T., Nagumo, M., Asano, I.: J. Jpn. Inst. Met. 42 (7), 708–715 (1978)
8) Sakamoto, M., Kodama, J.: The Proceedings of the 68th Japanese Joint Conference for the Technology of Plasticity. 11–12 (2017)
9) Teshima, T., Yamashita, T., Kosaka, M., Ushioda, K., Koga, N., Nakada, N.: Abstracts of The Japan Society for Heat Treatment 77th Conference. 77, 683–684 (2014)
10) Takahashi, J., Kosaka, M., Kawakami, K.,Tarui, T.: Acta Mater. 60 (1), 387–395 (2012)
11) Tarui, T., Maruyama, N., Takahashi, J., Nishida, S., Tashiro, H.: Shinnittetsu Giho. (381), 51–56 (2004)
12) Tarui, T., Maruyama, N.: Tetsu-to-Hagané. 90 (12), 1031–1037 (2004)


Masashi SAKAMOTO
Researcher
Bar & Wire Rod Research Lab.
Steel Research Laboratories
23-15 Suzuko-cho, Kamaishi City, Iwate Pref. 026-8567


Kenichi NAKAMURA
General Manager, Head of Dept.
Quality Management Dept.
Production Div.
Kamaishi Works


Toshihiko TESHIMA
Researcher
Kimitsu R & D Lab.