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State of the Art for High Tensile Strength Steel Cord

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Abstract

The tensile strength of steel cord, by which steel radial tire is reinforced, is steadily progressing in accordance with the need for lighter cars. 4,000 MPa class steel cord is commercialized by the improvement of ductility during wire drawing based on 0.9%C hypereutectoid steel wire rods. This report describes the strengthening concept, characteristics of strengthening method and micro-structure, improvement of ductility during wire drawing, maximum strength level, and future technical subjects.

1. Introduction

A steel cord used for reinforcing a radial tire is the strongest industrial material and has excellent ductility. Riding on the engine of motorization, its annual consumption has amounted to over one million tons all over the world. This is because of its excellent performance including safety, durability, and mobility[1)]. It is composed of 2 to 39 pieces of twisted, 0.15 to 0.38 mm brass plated steel wire which is drawn through tungsten carbide or diamond dies with wet lubrication. **Fig. 1** shows cross section of a steel radial tire.

Reflecting market needs for lighter weight and improvement of performance, the steel cord has been strengthened. Its tensile strength was about 2,800 MPa at 0.20 mm around 1970, 3,200-3,400 MPa in the 1980's but increased to 3,600 MPa early in the 1990's, and further to 4,000 MPa in around 1998[2-7)]. With the steel highly strengthened, the content of C for a steel cord wire rod increased from 0.7% in hypoeutectoid steel to 0.8% in eutectoid steel, and to 0.9% in hypereutectoid steel. This increase in strength is backed by the progress made in steel making technologies for reduction of center segregation and non-deformable non-metallic inclusions, for controlling pearlite structure excellent in drawability and a finished surface property by wire rod rolling and adjusted cooling, and for secondary processing as seen in patenting to control proeutectiod ferrite and cementite, and in wire drawing not to decrease the ductility of fine pearlite structure high in deformation resistance[2,3,7)].

This paper mainly describes the concept of strengthening, methods of strengthening, micro-structure features, technologies of improving ductility by secondary processing, strength levels achieved, and future technological subjects from the viewpoint of materials science.

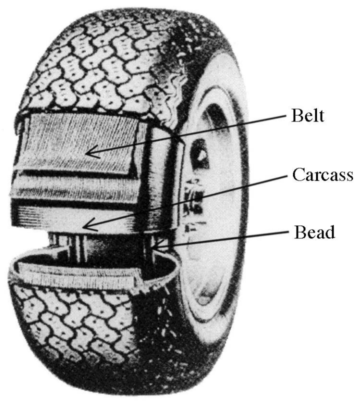

Fig. 1 Cross section of a steel radial tire

2. Concept of strengthening

Methods of strengthening pearlite steel wires include (1) increasing patented wire strength, (2) increasing the amounts of drawing strain, and (3) increasing the work hardening rate in wire drawing. In the strengthening of steel wires, those methods are combined in a satisfactory manner. **Fig. 2** shows a comparison of strengthening by patenting and wire drawing in the tensile strength of fine and thick diameter wire. In the steel cord of fine wire, the ratio of strengthen-

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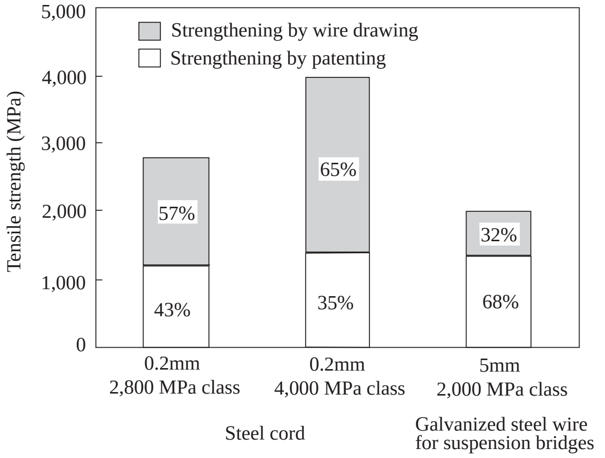

Fig. 2 Comparison of strengthening by patenting and wire drawing in the tensile strength of fine and thick-diameter high strength steel wires

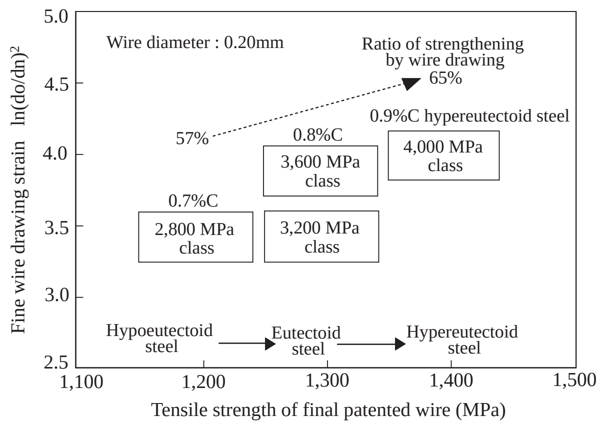

Fig. 3 Transitions of patented wire tensile strength and drawing strain when strengthening steel cords

ing by drawing exceeds 60%, and as the tensile strength increases, so does this ratio. It is necessary for strengthening to optimize the combination of highly clean high-carbon steel wire rods, low in center segregation and non-deformable non-metallic inclusions, with secondary processing technologies. **Fig. 3** shows the transitions of patented wire tensile strengths and drawing strains in the strengthening the steel cord. The drawing strain increases in line with the increases in the amounts of C and tensile strengths of patented wire. As the amount of C increases, so does the work hardening rate in the wire drawing. It becomes very important, however, to improve ductility by secondary processing since drawing becomes difficult.

Fig. 4 shows the relationship between wire diameter and tensile strength of steel cord. **Fig. 5** shows the changes of tensile strength and reduction of area in the drawing of eutectoid pearlite steel wires of varying diameters. Since drawability increases in proportion to a decrease in wire diameter, tensile strength can be rendered higher, which is a so-called size effect. However, this mechanism still remains un-clarified. Since the manufacturing cost in secondary processing increases as the wire diameter becomes finer, it has become necessary to increase tensile strength while maintaining ductility with the same wire diameter.

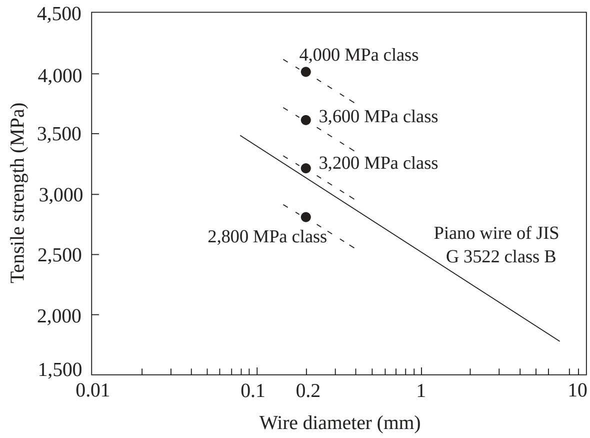

Fig. 4 Relationship between the wire diameter and the tensile strength of a steel cord (typical chart)

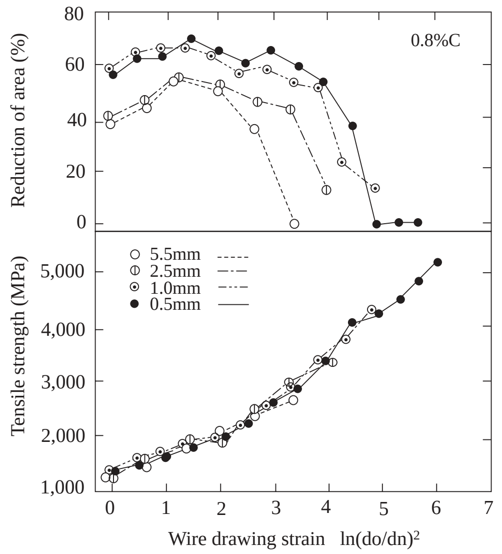

Fig. 5 Changes in tensile strength and reduction of area when drawing eutectoid pearlite steel wires of various diameters

3. Methods of strengthening and micro-structure features

The methods of strengthening steel can be broadly divided into solid solution hardening, dislocation strengthening, grain refinement strengthening, and precipitation hardening[8]. To the steel cord are applied dislocation strengthening (work hardening by cold deformation) and grain refinement strengthening (refinement of pearlite lamellar spacing). Recently the grain refinement of steel material for practical use are attracting our attention. It may be safe to say, however, that in a sense, the wire rod has taken advantage of strengthening by grain refinement from the earliest stage[9].

In order to strengthen pearlite steel, it is effective to make the pearlite lamellar spacing of patented wire finer, and increase tensile strength and work hardening rate while decreasing the strain of wire drawing as much as possible for the prevention of delamination[5]. It has become possible to estimate the strength of fine steel wire by formularizing work hardening during wire drawing[10]. **Photo 1** shows TEM micrographs of the 4,000 MPa class steel wire. It is apparent

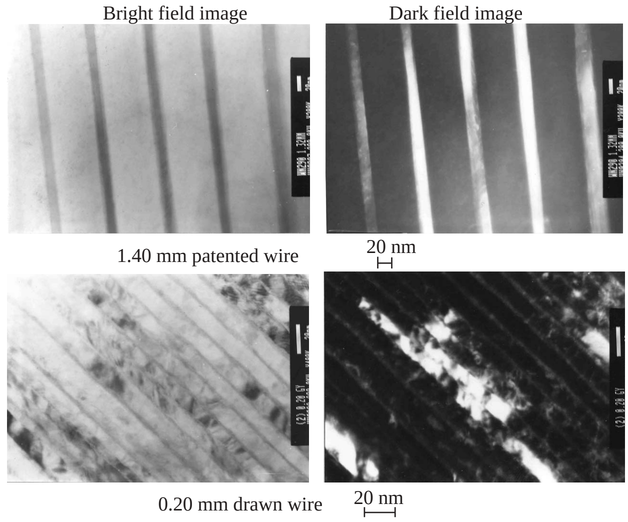

Photo 1 Transmission electron micrographs of patented and drawn wire in 0.9% C 4,000 MPa class steel cord

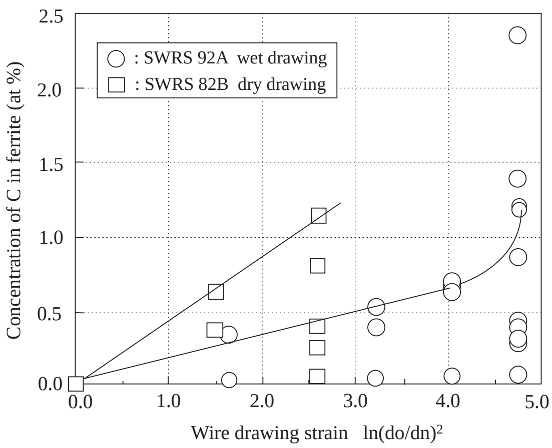

Fig. 6 Changes in concentration of C in ferrite during the drawing of pearlite steel wire

that cementite remains and that lamellar spacing is reduced to approximately 10 nm.

Attention has so far been paid to the minimizing of lamellar spacing in wire drawing. However, recent analyses of the Mössbauer effect, AP-FIM, and neutron diffraction have clarified the decomposition of cementite and supersaturated solid solution of C in ferrite. Energetic studies are under way with various hypotheses presented relative to the mechanism of cementite decomposition, the existence state of decomposed C atom, and the mechanism of strengthening[11-19]. **Fig. 6** shows the changes of the C concentrations in ferrite during drawing pearlite steel wire[19]. If cementite is decomposed and C concentration in ferrite increases as described above, the changes in mechanical properties due to strain aging cannot be ignored. Therefore, the analysis becomes necessary in terms of strain aging as well[20].

4. Technology for improving ductility through secondary processing

4.1 Concept of improving ductility through drawing fine wire

Since the ratio of strengthening by wire drawing is large for a steel cord, it becomes necessary to control the work hardening rate, uniform deformation, and cementite decomposition. In wire drawing, the amount of strengthening in radial direction is smaller than in axial direction[21], and the ratio of work hardening rate is larger as wire deformation becomes uniform. In die drawing, plastic deformation in the surface layer of steel wire differs from that in the center, resulting in non-uniform deformation. When non-uniform deformation is large, ductility decreases as seen in delamination. **Fig. 7** shows an example of the influence of the coefficient of friction on the uniform deformation of 0.30 mm fine steel wire. The distribution of hardness in the cross section was used as an index of uniform deformation. Deformation becomes more uniform as the difference is smaller in hardness between the surface layer and the center, resulting in the prevention of delamination. A decrease in the coefficient of friction not only promotes uniform deformation, but also lessens friction-induced heat generation to prevent cementite decomposition as well. It is necessary for ensuring ductility to pay attention to a carrier, a lubricant, a die material and shape, and one pass reduction.

4.2 The effect of brass plating carrier

When drawing fine wire, the action of carrier of brass plating greatly influences uniform deformation and friction-induced heat generation. In case of a steel cord, a fine wire is drawn after brass plating. However, the brass plating not only adheres to a rubber tire, but also acts as a carrier when drawing a fine wire[22]. **Fig. 8** shows the changes in Fe concentration on the surface when drawing a fine steel wire. As drawing strain increases, so does the concentration of Fe on the surface. When a wire is drawn, its specific surface area increases as its diameter decreases. This is because of the surfacing of Fe inside the wire as the brass plating is as thin as 2 to 3 μm. In proportion as the surface Fe concentration increases, the brass plating is hardened, accompanied by the deterioration of the action of the carrier. It is therefore effective for increasing drawing strain to thicken the brass plating while preventing an increase in surface Fe concentration for ductility improvement.

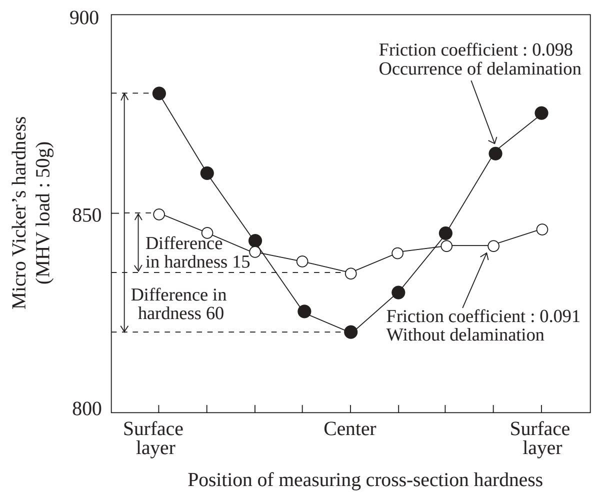

Fig. 7 Influences of the coefficient of friction on the cross-section hardness distribution of 0.30 mm fine steel wires

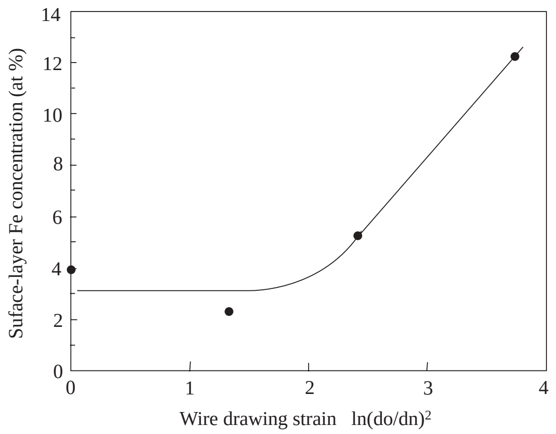

Fig. 8 Influences of wire drawing strain on concentration of Fe in surface layer of 0.30 mm brass-plated steel wire

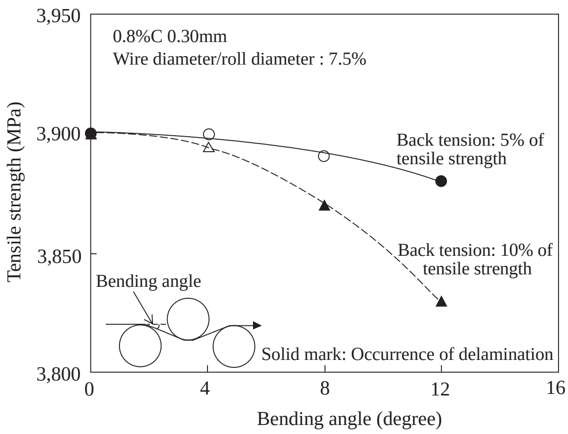

Fig. 10 Influences of roll straightening conditions on the tensile strength and delamination of a fine steel wire

4.3 Technology of promoting uniform deformation during drawing fine wire

One of the effective means of promoting uniform deformation during drawing a fine wire is to lower the angle of die approach. Lowering the angle from 14° to 10° lessens the difference in hardness between the surface layer and the center of the cross section. Furthermore, it is effective for the promotion of uniform deformation to draw a wire with its area reduction below 10% in the final pass. As **Fig. 9** shows, it is effective to combine a low approach angle die with low area reduction in the final pass. Again, the technology of improving ductility can be applied even after fine wire drawing. It is possible to achieve the same effect with that of promoting uniform deformation by decreasing a yield point and softening the surface layer through the technology of roll straightening. As **Fig. 10** shows, delamination can be prevented if the bending stress and back tension given can be controlled.

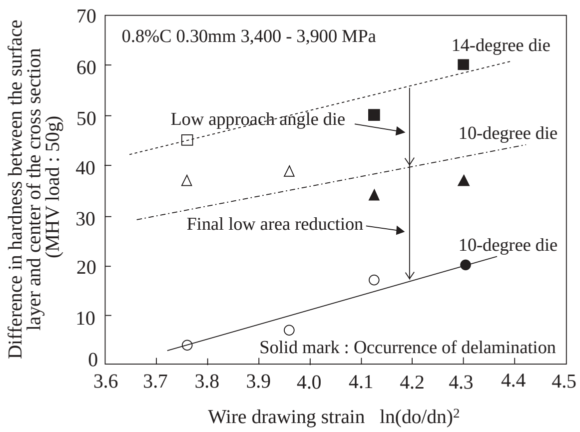

Fig. 9 Influences of die approach angles and final reduction of area on the cross-section hardness difference between the surface layer and center of brass-plated steel wire

5. Strength level achieved

As **Table 1** shows, highly ductile 0.20 mm - 4,000 MPa class steel with no delamination could be obtained by combining the 0.9%C hypereutectoid steel wire rod low in center segregation and non-deformable non-metallic inclusion with the technologies for ductility improvement through secondary processing, such as brass plating, the low approach angle die, and low area reduction in the final pass. Thanks to this 4,000 MPa class steel cord, steel came to be used for the carcass part of a passenger car tire for the first time[7]. Application to other part than the carcass part is also under study.

6. Future technological subjects

Economy is a determining factor in the employment of industrial materials. Not only strength but also ductility that can be put to practical use should be satisfied. There are various indices of steel wire ductility, including delamination, a torsion value, reduction of area, elongation, and kinks. However, delamination is adopted as a critical ductility index for a steel cord. The mechanism of the occurrence of delamination has not been clarified entirely. Cementite decomposition proceeds and C concentration in ferrite increases with the increase of true strain of wiredrawing. It is therefore necessary to prevent the deterioration of ductility due to strain aging caused by C.

Since the changes in pearlite steel structure form when drawing a

Table 1 Properties of 0.20 mm - 4,000 MPa class brass-plated steel wire

Kind of steel	Chemical compositions (mass%)						5.5mm wire rod quality		Mechanical properties of 0.20mm brass-plated steel wire			
	C	Si	Mn	P	S	Cr	Segregation index	Non-deformable non-metallic inclusion index	Tensile strength (MPa)	Torsion value (numbers, 1=100 d*) *d: Wire diameter	Delamination	Difference in hardness between the surface layer and the center of the cross section
SWRS 92A	0.92	0.22	0.48	0.014	0.008	-	0	1	4,012	27	None	15
92ACr	0.91	0.20	0.31	0.006	0.007	0.20	0	1	4,008	28	None	13

fine wire has not been clarified completely, it is vitally important to develop the analysis of a drawn pearlite steel wire at the nano level and the theory of strengthening for achieving a higher strength. If a wire diameter can be made finer, achieved strength can be enlarged, making it possible to achieve over 5,000 MPa strength for a wire diameter of less than 0.06 mm[23)]. Although systematic research has not been made thus far relative to size effect, there is a sign of new research being made recently[24)]. If those researches advance relative to pearlite steel, the quantitative discussion on the limit of strengthening will become possible[25,26)].

7. Conclusion

As described above, a steel cord has been greatly strengthened to a 4,000 MPa class for practical use. With the need growing increasingly for reducing the weight of automobiles, a steel cord should be strengthened still more so that it can outpace competing organic fibers, such as polyester and aramid. It is our sincere hope that the next-generation steel cord exceeding 4,500 MPa be realized early after the requirements of ductility have been grasped fully.

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