NIPPON STEEL TECHNICAL REPORT No. 80 JULY 1999

UDC 669 . 14 - 42

The Challenge for Maximum Tensile Strength Steel Cord

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Abstract

Steel cord used for tire reinforcement is the strongest industrial material. Strong demand for lighter weights propelled the steady increase in higher tensile strengths to the use of 0.20 mm/4,000 MPa class. Estimating from the boundary of high tensile strengths, higher tensile strength is possible with drawn pearlite steel. The following describes the features of the micro-structure of steel cord, size effect, limit of high tensile strength and the potential for future expansion from the view of developing maximum tensile steel strength.

1. Introduction

Various materials such as steel, non-ferrous, high-molecular materials and ceramics are used as construction materials, but the steel cord of piano wire used as the reinforcement for radial tires is the strongest industrial material known. Steel cord is a pearlite steel consisting of lamellar ferrite and cementite that has been strengthened by drawing and its strength is higher than high alloyed steel containing great amounts of high melting point metals such as W, Ni, Mo and Co.

The use of 0.20 mm 4,000 MPa class steel cords using a 0.9% C hypereutectoid steel has been propelled by the steady increase in higher tensile strength to respond to the need for lighter weights. Already, development with a view to using 5,000 MPa class steel cords is moving forward[1]. To the backdrop of increases in high tensile strength steel cord, progress has also been made in steel making technologies for reduction of center segregation and non-deformable inclusions and in secondary processing using improvements in wire ductility. This paper describes future expansions in the study of materials such as the micro-structure features of steel cord, size effects and the limit of high tensile strength.

2. Features of Steel Cord Micro-structure

In the strengthening of steel, methods include solid solution hardening, dislocation strengthening (work hardening by cold forming), intergranular strengthening (fine-graining) and precipitation hardening[2]. Hardening through cold drawing and finer pearlite lamellar spacing (called lamellar spacing below) are used in steel cords. Lamellar spacing of patenting materials is made finer in the strengthening of pearlite steel, and it is effective in increasing the tensile strength and work hardening ratio and in limiting drawing strain as much as is possible[1]. Lamellar spacing is the main controlling factor in the strength of pearlite steel, and it is possible to increase the limit of drawing strain by making lamellar spacing finer and by improving the degree of orientation of lamellar pearlite to ensure wire ductility[3,4].

Steel cord of fine wire differs from thick diameter wire in that the ratio of strengthening by drawing exceeds 55%, and as the tensile strength increases, so does this ratio. Along with a reduction in lamellar spacing and cementite thickness by drawing, there is an array in the direction of drawing to form a <110> fiber structure. Thin platelets of cementite in the steel have better plastic deformability. **Fig. 1**[5] shows the curve of work hardening by drawing of eutectoid steel and steel with other microstructures. The work

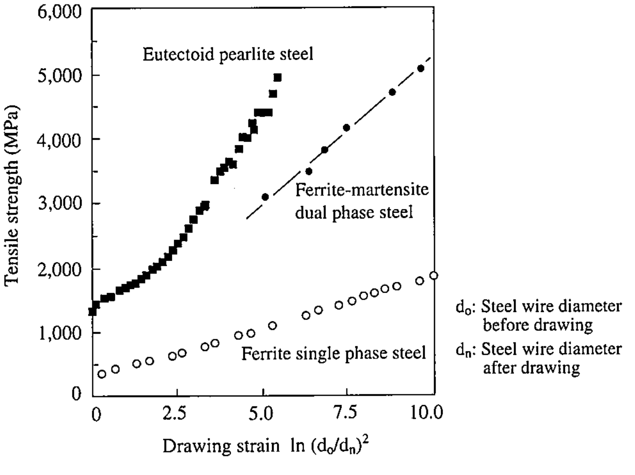

Fig. 1 Strengthening by drawing eutectoid pearlite steel, ferrite-martensite dual phase steel, ferrite single phase steel

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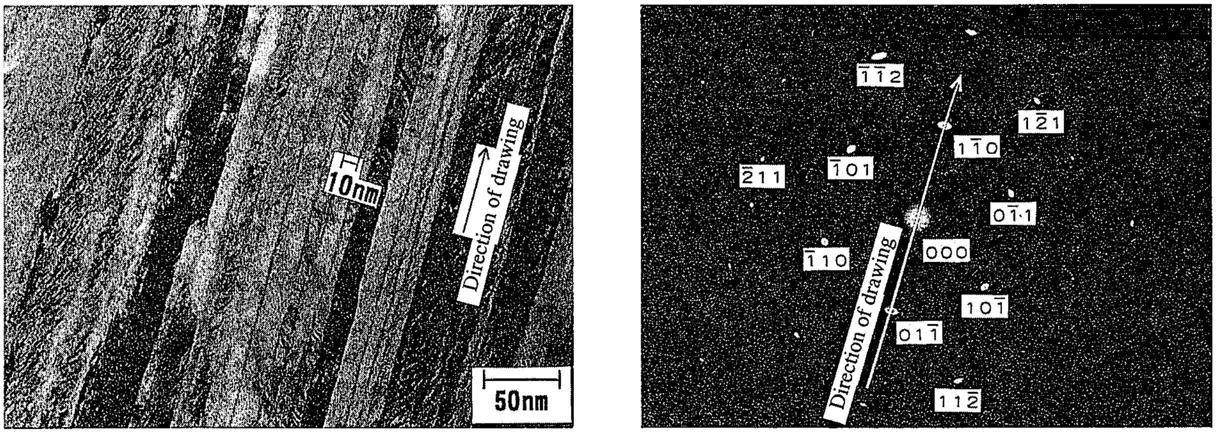

Bright field image

Selected-area electron diffraction pattern

Photo 1 Microstructure of 0.20 mm 4,000 MPa class brass plated steel wire as seen through transmission electron microscope

hardening ratio of eutectoid steel is greater than ferrite single phase steel that has low amounts of C, or dual phase steel comprising ferrite and martensite. A small drawing strain can produce high tensile strength in eutectoid steel. Not only is the tensile strength high for fine pearlite structure, but it also has good ductility. As **Photo 1** of 4,000 MPa class steel wire seen through a transmission electron microscope shows, there is no fragmentation of the cementite and the spacing of the lamellar is approximately 10 nm.

3. Size Effect

Because tensile strength is determined as force per unit of area (N/mm^2 = MPa), there is the tendency to always consider the effect of wire diameter. However, when considering the tensile strength of steel wire, the size of the diameter is extremely important. It becomes more difficult to attain uniform deformation when drawing as the diameter of the wire increases, which degrades the drawability and makes it difficult to strengthen the wire because drawing strain cannot be increased. As shown in **Fig. 2**[3)], the amount of work hardening is substantially the same with regard to drawing strain, so there is a tendency for reduction of area to decrease as wire diameters increase.

The relationships between the wire diameter of various high tensile strength materials and their tensile strengths are shown in **Fig. 3**[6)]. Perfect crystal whiskers can also be seen to be dependent on wire diameter, and there is a decrease in tensile strength as the size increases[7)]. This is because as size increases, the growing of perfect crystals becomes difficult. Both organic and inorganic fiber sizes are approximately 10 μm, so the tensile strength of piano wire becomes even more conspicuous when considering wire diameter. Amorphous wire, which is not a crystal, is lower in tensile strength than hypereutectoid steel piano wire and it is easily broken by torsion.

There is no progress in elucidating size effect as there has been only fragmental research [3, 8-10)]. It is considered that research regarding high tensile strength steel cords will be further propelled by clarification of the size effect.

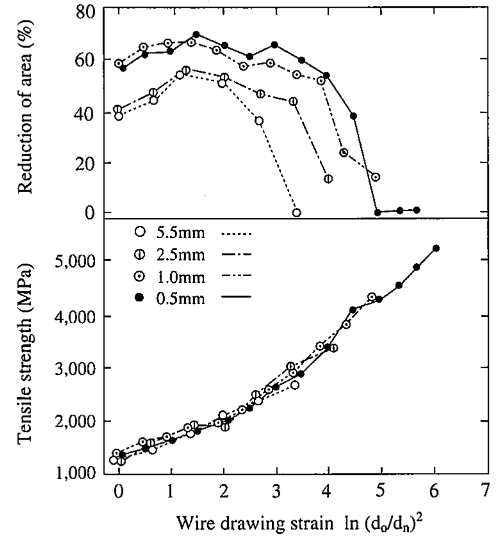

Fig. 2 Changes of tensile strength and reduction of area in wire drawing of eutectoid pearlite steel of varying sizes

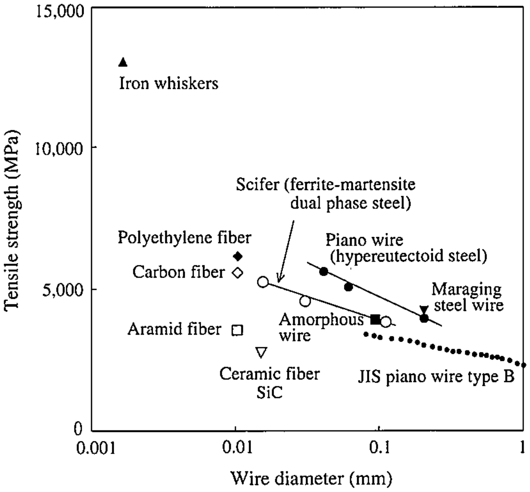

Fig. 3 Wire diameter of various high strength materials and tensile strengths

4. Limits of High Tensile Strength

There are two methods for attaining high tensile strength. They are the use of perfect crystals and imperfect crystals. Imperfect crystals are used as construction materials. Values between 10,000 and 13,000 MPa are theoretical for the strength of perfect iron crystals and actual measurements have been made of the strength using iron whiskers of several microns in diameter. Construction material including steel cord uses imperfect crystals having lattice defects such as dislocation, and it is extremely difficult to estimate the limits of high tensile strength. Using the limit values[2, 11] for dislocation strengthening, intergranular strengthening, solid solution hardening and precipitation hardening estimated by Takaki and Kawabe and estimating the limit of high tensile strength using simple additions of them leads us to the 11,500 MPa and 5,000 MPa values shown in **Table 1**. Because there is already tensile strength of 5,700 MPa using 40 μm pearlite steel wire[12], a high tensile strength limit of 11,500 MPa can be considered.

It was hypothesized that lamellar spacing is the main controlling factor in the limit of the high tensile strength of pearlite steel and it was estimated using the equation (1)[13].

$$TS = 1{,}000 + 26 \times l_p^{-1} \quad \cdots\cdots(1)$$

Here, TS is the tensile strength (MPa) of pearlite steel work-hardened by drawing.

l_p: Lamellar Spacing (μm)

As lamellar spacing grows smaller along with the work hardening by drawing, the thickness of the cementite grows thinner. When considering that the limit of deformation for cementite platelets is approximately 0.4 nm of the unit cell of the cementite crystal, the lamellar spacing at that time is approximately 3 nm and the tensile strength is approximately 10,000 MPa. Because dislocation strengthening and intergranular strengthening are approximately 10,000 MPa, there is much room for further strengthening of pearlite steel wire, and it is presumed that there will be higher tensile strength of steel cord in the future.

Because it is necessary for industrial material to be able to withstand actual usage conditions, it is necessary to have not only tensile strength, but also ductility. Steel cord has high tensile strength and is abundantly ductile. There are several indexes of the ductility of steel wires including delamination (a longitudinal crack observed in the drawing direction of steel wire when performing the torsion test.), torsion value, reduction of area and its elongation. There is some discussion regarding which of these is the critical index, but delamination is often used. It has been determined that there is an abundant ductility if delamination does not occur in the torsion test. Also, there is a tendency for misunderstanding that hardening by drawing is possible without limitation if ductility is ignored, but if ductility is greatly degraded, wires will break when being drawn from the die and there will naturally be limits to the maximum tensile strength attainable because work hardening by drawing will no longer be possible.

Table 1 Estimated strength (MPa) by strengthening element mechanisms

Element mechanism of strengthening	Takaki(1994)	Kawabe(1982)	Remarks
Dislocation strengthening	5,000	900	Limit to density of dislocation that can be introduced
Intergranular strengthening	2,000	600	Limit to fineness of crystal grain
Solid solution hardening	500	500	Limit to amount of solid solution hardening
Precipitation hardening	4,000	3,000	Limit to amount of precipitation
Limit of high tensile strength	11,500	5,000	Simple addition of element mechanisms of strengthening

5. Conclusion

As stated above, steel cords are the strongest known industrial material with superior ductility. There will be progress in the future for higher strengths as long as there is a need for lighter weights, which means that this is the front runner in the challenge for maximum tensile strength. Because the limit of tensile strength of pearlite steel drawn wire is estimated at approximately 10,000 MPa, in common with perfect crystals, it is possible to further strengthen steel cord.

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