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Strengthening of Steel Wire for Tire Cord

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Abstract:

To prevent the occurrence of delamination that hinders the strength increase of steel wire for tire cord, plastic anisotropy must be prevented from developing in the steel wire. It was found to be effective to this end to strengthen the patented wire and enhance work hardening in the drawing stage. A hypereutectoid chromium steel was developed according to these guideprinciples, and tire cord wire with a tensile strength of 3,600 MPa was successfully made from the new steel and put to practical use.

1. Introduction

The steel cord is the most important tire reinforcement and is used in more than 1 million tons per year throughout the world. The tensile strength of tire cord wire was initially 2,800 MPa and then increased to 3,400 MPa in the late 1980s, thanks to the progress of technology for reducing nonmetallic inclusions and center segregation[1]. The steady demand for reducing the tire weight to improve the fuel economy of automobiles resuted in mounting calls for steel cords with higher strength.

To meet the demand, the authors worked to develop tire cord wire with a tensile strength of 3,600 to 4,000 MPa, with the aim of attaining one-half of the theoretical limit of 10,000 MPa for the tensile strength of steel.

The desired strength of tire cord wire is obtainable by cold drawing piano wire. In principle, the strength of wire can be increased to any desired degree by increasing the extent of cold working. In reality, however, it is difficult to do so because the wire is found to lose its ductility with increasing strength with the result that it is cracked in the process of bunching. The development of technology for bunchability is a key to the strengthening of tire cord wire[1].

After clarifying the mechanism of wire cracking in the bunching stage and developing methods to prevent cracking, the authors succeeded in the development and commercialization of 3,600 MPa tensile strength tire cord wire. Realization of a tire cord wire with a tensile strength of over 4,000 MPa is already in sight. The details of these developments are described below.

2. Experimental Methods

Steels with varying contents of carbon and chromium, which are basic pearlite steel strengthening elements, were used as test materials. The chemical compositions of typical test steels are given in **Table 1**. Manganese has little strengthening effect, is likely to segregate at the center portion, and retards the pearlite transformation. Therefore, its content was held at a low 0.3%. Each steel was melted in a vacuum furnace in the laboratory or in a production furnace, and was rolled to a 5.5 mm diameter rod at a wire rod mill.

The patenting treatment was performed in a lead furnace. The

Table 1 Chemical compositions of test steels (wt%)

Steel	C	Si	Mn	Cr	P	S	Al
1	0.82	0.20	0.52	0.01	0.004	0.003	0.001
2	0.82	0.19	0.32	0.19	0.001	0.001	0.002
3	0.92	0.21	0.32	0.00	0.002	0.001	0.001
4	0.92	0.21	0.31	0.22	0.002	0.001	0.001
5	0.96	0.21	0.30	0.21	0.005	0.003	0.001

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heating temperature and time were 950°C and 80 s, respectively. The lead temperature ranged from 550 to 650°C. The rod was drawn dry to wire of 0.8 mm or more in diameter and drawn wet to less than 0.8 mm in diameter. The wet drawing speed was 600 m/min.

The lamellar spacing in pearlite was determined by the intercept method from 10 SEM micrographs, each taken at the magnification of 10,000×. The delamination is a crack that occurs in wire in the longitudinal direction immediately after yielding in torsion test. The occurrence of delamination can be detected by measuring the twist angle-torque curve of the specimen. **Fig. 1** is a twist angle-torque curve that shows the occurrence of delamination.

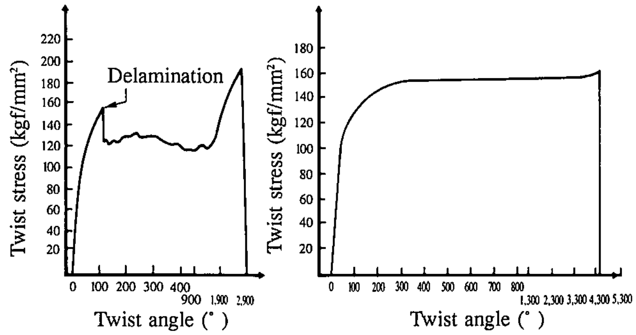
3. Experimental Results and Discussion

3.1 Key techniques for strengthening of tire cord wire

Fig. 2 shows the relationship between the frequency of break in bunching process and delamination characteristics of tire cord wire. A cord break occurs in the wire that delaminates. This means that the development of technology for preventing delaminations is a key to the strengthening of tire cord wire.

3.2 Guideprinciples for preventing delamination

The strength of tire cord wire can be increased by increasing the strength of patented wire and the total reduction of drawn wire[1]. **Fig. 3** shows the effects of wire strengthening methods on the delamination tendency of drawn wire. To obtain the same strength, increasing the strength of patented wire is preferred to increasing the total reduction of drawn wire from the point of view of delamination prevention.



(a) Delaminated wire (b) Non-delaminated wire

Fig. 1 Twist angle-torque curves

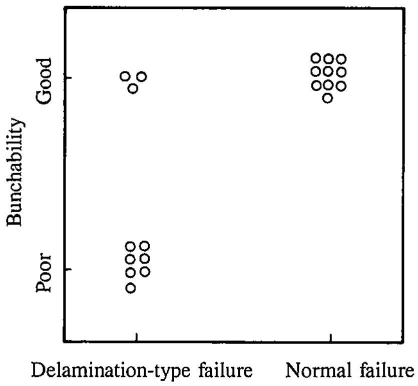


Fig. 2 Failure characteristics of tire cord wire

This is an important result according to which guideprinciples can be developed for increasing the strength of tire cord wire. The underlying reason was analyzed to establish more universal guideprinciples for preventing the delamination of tire cord wire.

When drawn to a strain level exceeding the true strain of 1, wire has the <110> fiber texture, and its grains become elliptical. The slip systems of the wire are illustrated in **Fig. 4**[2,3].

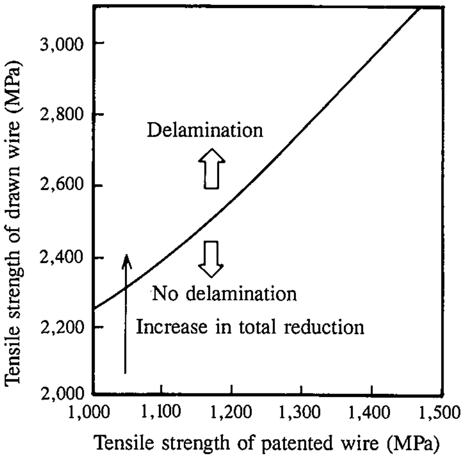
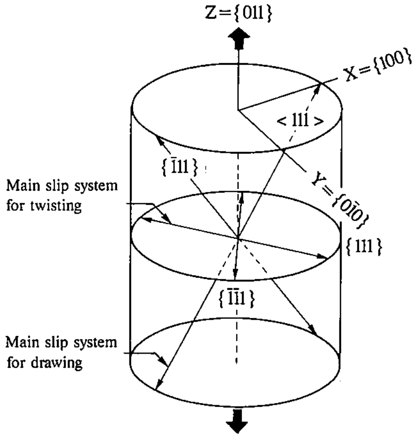
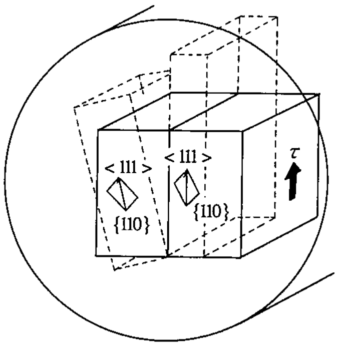


Fig. 3 Effects of tensile strength of patented wire and total reduction of drawn wire on tensile strength until delamination occurrence



< 111 > direction in {011} fiber texture



—Before deformation, -- After deformation
Schematic diagram of grain deformation in twisting

Fig. 4 Slip systems of steel wire with <110> fiber texture and deformation behavior of grains in twisting

When the wire is twisted, two <111> slip systems within the plane normal to the drawing direction act to initiate the torsional deformation of the wire. Since adjacent grains differ from each other in the direction of deformation, they need additional rotational deformation in which one follows the other, in order to maintain the intergranular compatibility. As iron can slip only in the <111> direction, the rotational deformation is caused by the operation of the slip system in the drawing direction.

If the rotational deformation required to secure compatibility between the neighboring grains cannot follow the main deformation that proceeds within the plane normal to the drawing direction, a crack occurs between the grains, leading to a delamination.

As the flow stress in the slip system in the drawing direction becomes higher than that in the slip system within the plane perpendicular to the drawing direction, it becomes more difficult for the rotational deformation to follow the torsional deformation, thus giving way to occurrence of delamination.

The flow stress in the slip system in the drawing direction is evaluated by the yield stress (σ_y) in the tensile test, and the flow stress in the slip system within the plane perpendicular to the drawing stress is evaluated by the yield stress (τ_y) in the torsion test. **Fig.** 5 shows the changes in the yield stresses σ_y and τ_y with the increase of total drawing strain. Flow stress in the slip system in the drawing direction steeply increases with work hardening due to drawing, while that in the slip system normal to the drawing direction only slightly increases because the slip system is used only in the additional rotational deformation[4]. As can be seen from **Fig.** 5, σ_y is higher than τ_y for wire drawn with higher total reduction to obtain the same strength level. This finding is arranged as the relationship between τ_y and σ_y in **Fig.** 6.

For the prevention of delamination, increasing the strength of patented wire is more favorable than increasing the total reduction of drawn wire because the occurrence of delaminations is governed by the easiness of the rotational deformation in which grains in torsional deformation can follow adjacent grains.

Since the imbalance between τ_y and σ_y increases with increasing total reduction, increasing the work hardening of drawn wire as well as the strengthening of patented wire is preferable in reducing the delamination tendency of drawn wire.

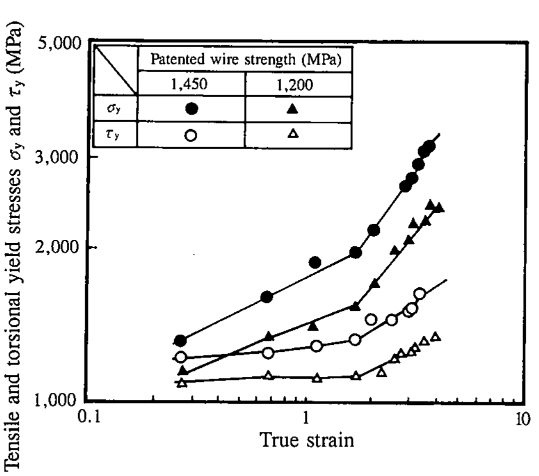


Fig. 5 Changes in tensile and torsional yield stresses with increase in total reduction

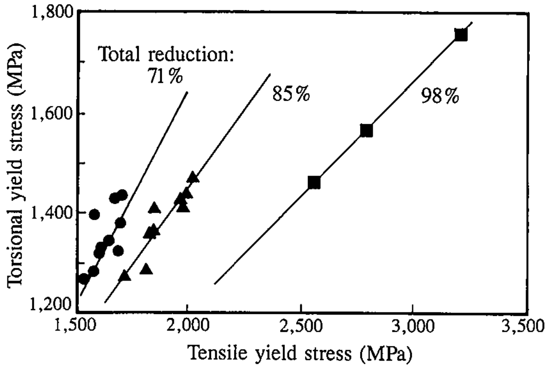


Fig. 6 Tensile yield stress versus torsional yield stress

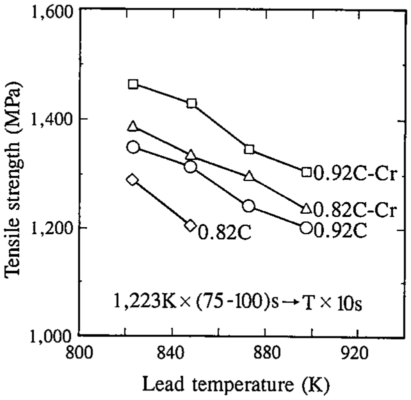


Fig. 7 Effects of carbon content and chromium addition on strength of patented wire

3.3 Development of methods for increasing strength of patented wire and enhancing work hardening

Methods for increasing the strength of patented wire and enhancing work hardening in the drawing stage were studied first. **Fig.** 7 shows the effects of carbon content and chromium addition on the strength of patented wire. The chromium addition is very effective in increasing the strength of patented wire as is known well, and increasing the carbon content is also effective. When the austenite-to-pearlite transformation is conducted at 575°C, a strength increment of about 90 MPa is obtained by increasing the carbon content from 0.82 to 0.92%. Carbon and chromium both act to reduce the pearlite lamellar spacing[5].

The work hardening of drawn wire increases with decreasing lamellar spacing of pearlite. The pearlite lamellar spacing being equal, work hardening increases with increasing carbon content as shown in **Fig.** 8[5,6]. This is probably because the increase of carbon content decreases the thickness of the ferrite layer where dislocations move, even if the pearlite lamellar spacing is the same.

According to these results, the authors designed the chemical composition of a new steel for high-strength tire cord wire with carbon increased and chromium added[5].

Fig. 9 shows the effect of the patenting temperature on the strength and microstructure of the 0.96%C-0.2%Cr steel. When the transformation temperature falls below 560°C, a degenerated pearlite appears at grain boundaries. The degenerated pearlite

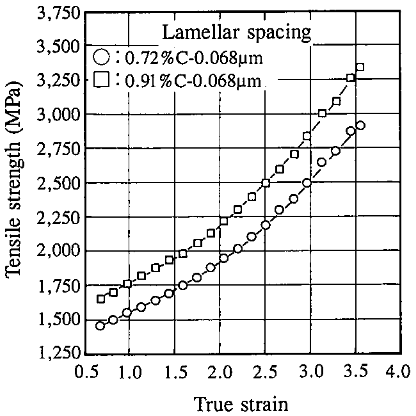


Fig. 8 Effect of carbon content on work hardening characteristics of pearlite steel in drawing

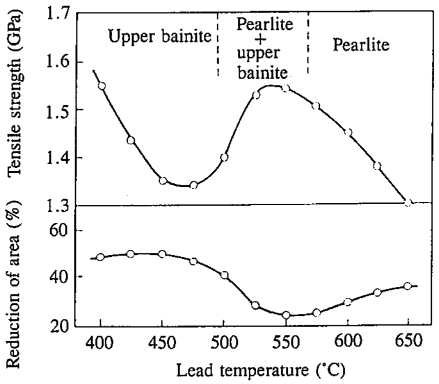


Fig. 9 Effect of patenting temperature on strength and microstructure of hypereutectoid steel (steel 5 in Table 1)

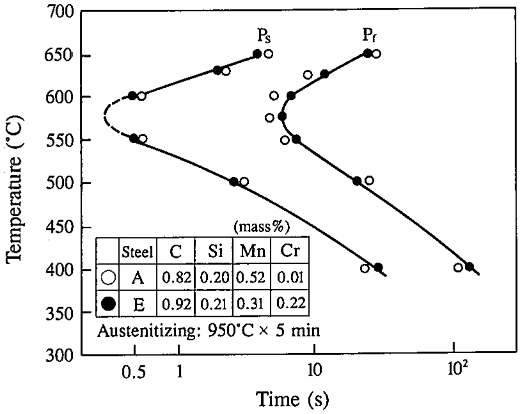


Fig. 10 Transformation characteristics of hypereutectoid chromium steel

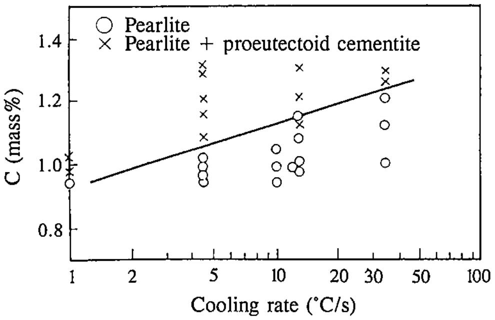


Fig. 11 Effect of cooling rate on precipitation of proeutectoid cementite in hypereutectoid chromium steel

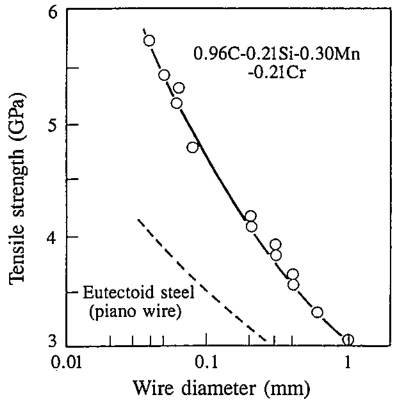


Fig. 12 Ultimate strength of hypereutectoid steel wire

reduces the ductility of grain boundaries, leading to the occurrence of delamination. The maximum strength of patented wire that can be achieved with this steel is about 1,500 MPa on condition that the degenerated pearlite does not appear. This strength is about 150 MPa higher than that of the conventional 0.82%C tire cord steel.

Fig. 10 shows the transformation characteristics of the 0.92%C-0.2%Cr steel in comparison with the 0.82%C steel. Chromium additions of up to 0.2% hardly retard the austenite-to-pearlite transformation, causing no productivity problem[5].

Increasing the carbon content is liable to encourage the formation of proeutectoid cementite, particularly when the cooling rate from the austenite region is slow. **Fig. 11** shows the effects of the carbon content and the cooling rate from the austenite region on the formation of proeutectoid cementite. When cooled by the Stelmor cooling process that provides a cooling rate of 10 to 15°C per second, a 5.5 mm diameter rod has no proeutectoid cementite formed at the carbon content of up to 1.1%[5].

Fig. 12 shows the relationship between the wire diameter and the tensile strength of drawn wire that can be achieved with the 0.96%-0.2%Cr steel on condition that no delaminations occur. The tensile strength is 5,000 MPa for the wire diameter of 80 μm and 4,000 MPa for the wire diameter of 0.2 mm. Tire cord wire with the tensile strength of 3,600 MPa is already commercialized and used in actual tires.

4. Conclusions

The delamination that critically effects the strength of tire cord wire arises from the plastic anisotropy of crystallographic grains. The strength of tire cord wire must be increased while suppressing the development of anisotropy. It has been made clear that increasing the strength of patented wire and enhancing the work hardening of drawn wire are effective in increasing the strength of tire cord wire. Increasing the carbon content and adding chromium were found to be effective means of increasing the strength of patented wire and enhancing the work hardening of drawn wire. A hypereutectoid chromium steel was developed as a new steel for high-strength tire cord wire. Using the newly developed steel, tire cord wire with a tensile strength of 3,600 MPa was successfully commercialized. The strengthening of tire cord wire will continue along with the search for the ultimate strength of iron. Economics will be emphasized more than ever in the development of tire cord wire of still higher strength. We will accelerate our work on the development of tire cord steel and fabrication technology according to the delamination prevention guideprinciples established here, in order to meet the demand for tire cord wire of much higher tensile strength.

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