Microstructure and Mechanical Properties of Ultra-High Strength Pearlitic Wire in Single-pass Cold Drawing

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Abstract. The effect of compression ratio on the microstructure and mechanical properties of ultra-high strength pearlitic wire in single-pass cold drawing has been studied. The ultra-high tensile strength cord steel with a carbon content of 1.02 wt% were pulled through a single-pass drawing to different compression ratios (0-30%). With the increase of the single-pass compression ratio, the tensile strength, microhardness and torsional properties of the steel wire increased gradually. When the compression rate increased from 0 to 30%, the tensile strength of the steel wire increased from 1263.4 MPa to 1553.7 MPa, the torsional strength of steel wire increased from 1126.83 MPa to 1279.66 MPa. In the single-pass drawing process, the strengthening mechanism of the pearlitic steel wire are mainly the work hardening caused by the dislocation slip in the ferrite, and the fine grain strengthening caused by the decrease of the pearlite sheet spacing.

1. Introduction
Pearlitic steel wire of high-strength is a nano-crystalline structure metal material which is obtained by strong plastic deformation [1]. And now pearlitic steel wires are applied to engineering applications in large-scale. Among them, Development of steel wire for cold-drawing bridge cables and steel cords for radial tires are toward to positive high strength and ultra-high strength [2-3].

Radial tires replace oblique rubber tires was a major revolution in car tires. Radial tires have the advantages of good wear resistance, low rolling resistance, fuel economy, good cushioning performance, good heat dissipation, high speed, high safety and reliability [4]. According to different materials of carcass and belt of tires, radial tires can be divided into three types: all steel radial tires (TBR), semi-steel radial tires (PCR) and all-fiber radial tires [5]. There are many researches on pearlitic steel wire containing 0.82% carbon and 0.92% carbon at home and abroad, but fewer studies and reports on the mechanical properties and microstructure of ultra-high tensile strength steel wires in single-pass cold drawing have been carried out. In this paper, the hypereutectoid pearlitic steel wire with carbon content of 1.02wt% was used as the raw material, and the mechanical properties and microstructure evolution of the steel wire with different strains in the single-pass drawing process were studied.

2. Materials and method
The object studied here is an ultra-high tensile strength cord steel with a carbon content of 1.02 wt%.

The sample preparation process is mainly to pull Φ5.5mm wire rods through a single-pass drawing to different compression ratios (10%-30%). The chemical composition of 1.02 wt% pearlitic steel wire used in the test is shown in table 1:

| Element | Content (wt%) |
|---------|--------------|
| C       | 1.02         |
| Si      | 0.215        |
| Mn      | 0.310        |
| P       | 0.0089       |
| S       | 0.0041       |
| Cr      | 0.297        |

First, the steel wire was cut into small pieces. After polished and etched, they were observed with a metallurgical microscope. Corroded samples were observed under scanning electron microscopy (SEM) for the microstructure of the pearlite and the pearlite wire spacing was measured also. In this paper, transmission electron microscopy (TEM) was used to observe the change of pearlite lamellae and cementite lamellae and the distribution of dislocations in ferrite with increasing drawing strain.

When performing tensile strength test, the gauge length of the tensile sample was selected to be 100mm, and the tensile strain rate was 10mm/min. The experimental parameters of the torsion test in this article were determined according to the national standard and the actual test conditions.

3. Result

3.1 The metallographic microstructures of ultra-high tensile strength cord steel

Because the pearlite grains are very small, the scanning electron microscope with higher resolution was used to observe the change of the microscopic morphology of the steel wire with different compressibilities. The SEM image of initial wire rod is shown in figure 1. From figure 1, it can be seen that there are obvious lamellar structures and pearlite groups, and the lamellar orientation between adjacent groups of pearlite is random.

![Figure 1. SEM image of initial wire rods: (a) Cross section; (b) Longitudinal section](image)

The SEM images of steel wires with different compression ratio of 10% and 30% in the cross section is shown in figure 2. According to the figure, it can be seen that with the increase of the strain in the single-pass drawing, part of the pearlite sheet has seen bent and folded, as shown by the arrows in the figure. At the same time, the distance between layers of pearlite became smaller.
Figure 2. The SEM images of steel wires with different compression rates in the cross section: (a) Compression rate is 10%; (b) Compression rate is 30%

The TEM images of hypereutectoid pearlitic steel wires with a carbon content of 1.02% is shown in figure 3. Obvious pearlite sheets can be seen in the figure, the black area is a cementite sheet and the bright white area is pearlite. Comparing figure 3(a) and figure 3(b), it can be clearly seen that, compared to the initial steel wire, the pearlite sheet spacing decreases and the cementite sheets are thinned as the compression ratio increases. Besides, minor deformation has appeared in the cementite sheet. However, due to the strain is small, the change is not obvious.

The TEM images of the cementite sheets at a compression rate of 30% is shown in figure 3(c). Figure 3(d) is an enlarged view of the red block in figure 3(c). The cementite sheets in the figure 3(d) are clear and intact, with no fragmentation, indicating that cementite did not fragment when the strain was small.

3.2 The mechanical properties of single-pass drawing steel wire
The initial diameter of wire rods used for single-pass drawing is 5.5 mm. The tensile strength of steel wires under different drawing strains are listed in table 2. In order to clearly show the relationship between tensile strength and strain, the data in the table is plotted as a curve as shown in figure 4. From the figure, it can be seen that as the strain for single-pass drawing increases, the tensile strength of the pearlitic steel wire slowly increases first, then increases rapidly, and gradually tends to be flatten finally. When the compression ratio of the steel wire increased from 0 to 30%, the tensile strength of the steel wire increased from 1263.4 MPa to 1553.7 MPa, and the tensile strength increased by 22.98%.
Table 2. Relationship between tensile strength and compressibility of single-pass drawing steel wire

| Compression ratio (%) | Strength (MPa) |
|-----------------------|---------------|
| 0                     | 1263.4        |
| 10                    | 1267.3        |
| 15                    | 1281.5        |
| 20                    | 1468          |
| 25                    | 1537          |
| 30                    | 1553.7        |

Figure 4. Relationship between tensile strength and compression ratio of Single-pass drawing steel wire

The results of torsion test of the single-pass drawing steel wire are shown in table 3. The number of torsion turns of the original wire rod was 15 and the torsional strength was 1126.83 MPa. From the data in the table, it can be seen that as the single-pass drawing compression rate increases, the number of twisted turns of the steel wire gradually increases, and the torsional strength also increases. When the compression rate increased from 10% to 30%, the number of torsional turns of the steel wire increased from 15 to 21 turns, and the torsional strength increased from 1137.31 MPa to 1279.66 MPa.

Table 3. The torsion test results of single-pass drawing steel wire

| Compression ratio(%) | Diameter(mm) | Torsional turns | Torsional strength(MPa) |
|----------------------|--------------|----------------|-------------------------|
| 0                    | 5.5          | 15             | 1126.83                 |
| 10                   | 5.22         | 15             | 1137.31                 |
| 15                   | 5.07         | 15             | 1142.94                 |
| 20                   | 4.92         | 18             | 1175.76                 |
| 25                   | 4.76         | 18             | 1176.77                 |
| 30                   | 4.60         | 21             | 1279.66                 |

4. Discussion

4.1 Effect of strain on microstructure in single pass drawing

From the results of SEM and TEM, it can be seen that with the increase of the strain, the interlamellar spacing of the pearlite groups became smaller, the alternating cementite and ferrite layers in the pearlite deformed at the same time. Pearlite is the product of the eutectoid reaction in the Fe-C binary system. The ferrite in the pearlitic steel is a solid solution of C in Fe and belongs to the body-centered cubic structure. It has good plasticity and can achieve plastic deformation at high temperature. However, cementite is a hard and brittle M3C interstitial compound. Traditional physical metallurgy believes that such mesophases cannot be plastically deformed at room temperature. The previous literature reported [6-8] that when the pearlitic steel was cold-worked, only the ferrite was deformed in the microstructure, and the cementite was not deformed. If the stress was high, the cementite layer would cracked and crushed. In recent years, in the literature on the study of the microstructure of large
deformation of cold-drawn steel wire [9-11], the observation results of simultaneous deformation of cementite and ferrite have been reported, and this is referred to as “coordinated deformation”.

4.2 Effect of strain on mechanical properties in single-pass drawing
Pearlitic steel belongs to high carbon steel and its strength is higher than that of mild steel mainly due to the "second phase" strengthening of cementite. In this paper, the tensile strength, torsional strength and hardness of the pearlitic steel wire increased with the drawing strain after single-pass drawing, but the plasticity decreased a lot. This is similar to the change in mechanical properties of ordinary metal materials during deformation processing. For metallic materials of cubic structure, strengthening after cold working is generally attributed to "work hardening." In this paper, this strengthening process occurs only in ferrite.

The crystal structure of ferrite belongs to the typical body-centered cubic structure. The deformation of the cubic metal is mainly controlled by the slip mechanism. In the single-pass drawing process, when the external force reached the critical resolved shear stress of ferrite, one of the slip system of ferrite began to slip. At this time, ferrite was in a single slip state, dislocations increased a lot and the dislocations slide along a certain direction in a certain sliding plane. Since the dislocations were prone to slide at this time, the resistance is less, so the steel wire strength increased slowly when the compression ratio was small. As the compressibility and the critical shear stress increased, multiple slip systems in ferrite started. At this point, the resistance to dislocation movement increased, making the slipping process more difficult. At the macro level, the plasticity was reduced and the strength was improved. The TEM images of the steel wire with 10% compression rate and 30% are shown in figures 5(a) and (b). Comparing the two figures, it can be seen that the density of dislocations in ferrite increased significantly as the compressibility changed.

![Figure 5](image.jpg)

**Figure 5.** The dislocation changes of 1.02wt% wires for different compression rates

(a) The compression rate is 10%; (b) The compression rate is 30%

In addition to the deformation hardening of ferrite, fine-grain strengthening is also produced during the deformation of cold-drawn pearlite. From the TEM images shown in figure 5, the pearlite lamellar spacing decreased as the strain increased. According to Hall-Petch formula, it can be seen that the smaller the pearlite sheet spacing, the higher the steel wire strength. Therefore, the decrease of the spacing between pearlite layers due to cold drawing deformation is also one of the factors causing steel wire strengthening.

5. Conclusion
With the increases of the single-pass compression ratio, the microstructure of the wire changes. The pearlite bends and folds on the cross-section and the pearlite structure undergoes coordinated deformation on the longitudinal section. The pearlite sheet spacing is slightly reduced, the cementite sheet is thin and slightly deformed, but the cementite sheet remains intact at this time. With the increased of the single-pass compression ratio, the tensile strength and torsional properties of the steel
wire increased gradually. When the compression rate increased from 0 to 30%, the tensile strength of the steel wire increased from 1263.4 MPa to 1553.7 MPa, the torsional strength of steel wire increased from 1126.83 MPa to 1279.66 MPa. In the single-pass drawing process, the strengthening mechanism of the pearlitic steel wire are mainly the work hardening caused by the dislocation slip in the ferrite, and the fine grain strengthening caused by the decrease of the pearlite sheet spacing.

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