Cause analysis and prevention of fish scale crack defect for steel cord

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Abstract. In the production process of a steel cord, for the surface defect of steel wire with a diameter of 3.42mm in the heavy-duty-drawing process of a semi-finished product, macro and micro-analysis were carried out, and the defect causes were verified through production field tests. It has shown that the unprotected hard collision during the transportation and the shoveling after arriving at the factory results in damages to the surface of the wire rod, which cause high temperature from the friction with the drawing die during the drawing process leading to the appearance of drawing martensite, and it eventually leads to the surface defects of the steel wire. Based on the reasons above, comprehensive preventive measures were formulated to reduce the frequency of occurrence for the surface defects on the steel wire.

Keywords: steel cord, steel wire, fish scale crack, drawing martensite.

1. Introduction
The production process in a steel cord factory is as follows: 6-time-process cold-drawing for Φ5.5mm wire rod to obtain Φ3.42mm heavy-duty-drawing steel wire, 12-time-process medium-duty-drawing to obtain Φ2.04mm steel wire; austenization by heating, then subjected to sorbitizing treatment of AQ solution, copper plating, galvanization, medium-frequency thermal diffusion to form a brass alloy layer to obtain semi-finished yellow wire[1]. In the wet drawing area, a wet drawing at a speed of 600 to 1000 m/min is performed to obtain a Φ0.15~0.38mm monofilament, and a torsional stress is applied to the monofilament to obtain a steel cord. If the surface of the steel wire produced in the semi-finished area is defective, wire breakage will occur during wet wire drawing or cord production, seriously affecting the production efficiency and leading to failure of the steel cord[2-3]. During the production process of a steel cord, fish scale crack defects on the surface are often found during the inspection of the heavy and medium-duty-drawing products under a 50-time-magnification optical microscope. These
defects often appear in batches when switching wire rods from different manufacturers. When these defective semi-finished yellow wire goes into the next wet drawing process, the wire breakage rate in the wet drawing process will show a clear upward trend. In order to solve this problem, the macroscopic morphology of surface defects and metallographic structure of Φ 3.42mm heavy-duty-drawing steel wire were inspected in this paper, then the verification experiments at the production site was conducted to confirm the direct cause of the defects. According to the reasons determined, preventive measures and suggestions are given later.

1.1. Inspection of defect shape

The batch of wire rods with drawing surface defects were drawn from the Φ5.5mm wire rod to the Φ3.42mm through heavy-duty-drawing equipment. Three steel wires with a length of about 1 meter were collected to the laboratory for macroscopic and microscopic morphology inspection and analysis.

After the 6-time-process cold drawing of the Φ5.5mm wire rod, the macroscopic morphology of the surface fish scale cracks for Φ3.42mm steel wire are shown as in Fig. 1. As shown in Fig. 1(a), the continuous squamous crack defects on a 1-meter-long steel wire are 13cm long. With the 50-time-magnification optical microscope, as shown in Fig. 1(b), the fish scale cracks spread over the axial direction of the surface of the heavy-duty-drawing wire.

![Fish scale crack defect with a length of 13cm](Fig.1) (b) Fish scale crack defects after 50 times magnification

1.2. Analysis of the metallographic structure of the fish scale crack

The 13cm-long heavy-duty-drawing steel wire with fish scale cracks observed above was cut off and cut into 6 segments at a length of 2cm per segment using the Q-2A metallographic sample cutter produced by Jinan TENSION Experimental Machine Co., Ltd. The end face of the 6-segment heavy-duty-drawing wire was placed parallel to the base of the automatic mounting machine to complete the production of standard samples. Grinding and polishing were carried out using the grinding and polishing machine, then 4% nitric acid alcohol was used to corrode the metallographic structure. A white bright layer with a thickness of about 9μm was observed under the optical metallurgical microscope, as shown in Figure 2. Xu et al [4] suggested that the transverse cracking of the bright layer on the steel wire surface is the deformation martensite produced during the drawing process based on their research on the deformation martensite in the production process of wire products. It is known that the fish scale cracks on the surface of the wire are martensite based on the comparison methods.
Fig.2 Drawing martensite at the site of fish scale crack

2. Causes analysis

2.1. Causes analysis of drawing martensite

The metallographic structure of a normal steel cord wire rod is pearlite, and the heavy-duty-drawing steel wire obtained after 6-time-process drawing should be a fibrous pearlite structure. According to the phase transformation theory, to obtain the martensite structure, the surface temperature of the heavy-duty-drawing steel wire must reach the austenitizing temperature, and then rapid cooling should occur. Under normal circumstances, the wire rod is processed as: mechanical dephosphorization $\rightarrow$ pickling $\rightarrow$ coating with boron $\rightarrow$ surface saponification $\rightarrow$ drawing $\rightarrow$ heavy-duty-drawing of the finished steel wire, in which the saponification plays a lubricating role. Due to the lubricating effect of soap powder between the steel wire and the drawing die and the water cooling device in the die box, although the temperature on the surface of the steel wire has a phenomenon of temperature rise, the temperature of the heavy-duty-drawing wire at the die outlet does not exceed 100°C via temperature measurement on site under normal circumstances. Through laboratory examination, it has revealed that the drawing martensite appears intermittently on the steel wire, which does not exist on the entire steel wire circumference. These phenomena indicate that, the lubrication of soap powder under normal circumstances can reduce the friction between the wire rod and the drawing die, thereby avoiding the excessive heating of the steel wire surface and causing the drawing martensite on the steel wire surface. Liu et al. [5] believes that when the friction force between the wire rod and the drawing die is too large due to poor lubrication, the heat generated by the friction can cause the surface temperature of the heavy-duty-drawing steel wire to rise instantaneously to above 700°C; Meanwhile, there is a large compressive stress between the heavy-duty-drawing steel wire and the drawing die causing the temperature of the austenite transformation point to move down. These two factors lead to the austenite transformation of the local surface area of the heavy-duty-drawing steel wire during the drawing process. After the heavy-duty-drawing steel wire is completed, the steel wire enters the cooling stage again. Since only the local surface area of the steel wire experiences the austenite transformation because of high temperature, and the temperature of most of the adjacent steel wires does not exceed 100°C. In this case, the cooling rate of the high temperature area on the steel wire surface is very fast, and the cooling rate exceeds the critical point for the martensite transformation. The combined effect of these factors leads to the production of drawing martensite on the surface of the heavy-duty-drawing steel wire. In the subsequent drawing process, since the plasticity of the martensite structure is much lower than that of the pearlite structure,
the martensite on the steel wire surface is snapped during the drawing process, resulting in the formation of fish scale crack.

2.2. Reason analysis of the lubrication failure during drawing

From the discussion and research above, it can be seen that lubrication failure is the cause of production of drawing martensite during the drawing process. According to the on-site inspection and analysis of the production workshop, the reason for the lubrication failure during the drawing process is presumably due to the various mechanical damages on the wire rod surface before drawing, as shown in Figure 3: (a) macroscopic morphology photo of the mechanical damage before the wire rod is placed; (b) morphology photo of the mechanical damage of the wire rod after mechanical dephosphorization using phosphorus removal box; (c), (d), (e), (f) 50-time-magnification morphology photo of the mechanical damage of the wire rod after pickling. It is concluded that these mechanical damages on the wire rod surface will lead to the lubrication failure of the soap powder during the drawing process based on comprehensive analysis.

![Mechanical damage on the surface of wire rod before drawing](image)

**Fig.3** Mechanical damage on the surface of wire rod before drawing

3. Verification experiment of drawing martensite resulting from the surface damage

The following production field experiment was conducted to verify that the mechanical damage on the surface of the wire rod is the direct cause of the drawing martensite on the surface of the heavy-duty-drawing steel wire. The specific test process is as follows: 1. Find a wire rod with mechanical damage on the surface of the wire drawing area of No. A0101 unit, as shown in Figure 4(a); 2. Use copper sulfate on both sides of the wire rod for a coating that is about 20cm for marking, as shown in Figure 4 (b); 3. Start up for drawing and sample the marked area; 4. Check the surface quality in the laboratory.
Based on the laboratory testing, it is shown that no fish scale cracks generate in the non-damaged area, and fish scale cracks show its presence in the mechanically damaged area as shown in Figure 5. According to the previous analysis, it is known that the drawing martensite are generated during the drawing process. Through the verification experiments above, it is proved that the direct cause for the production of drawing martensite is due to the mechanical damage on the wire rod surface, which leads to the lubrication failure and subsequent austenization because of instantaneous temperature rising resulting from frictional heat generation, and then the rapid cooling causes the production of martensite on the surface. In the subsequent drawing, the martensite structure has a lower plasticity than pearlite, leading to the generation of fish scale cracks.

Comparison of oxidized scale of domestic wire rod and wire rod produced by Nippon Steel. According to the statistical report of the surface inspection of the heavy-duty-drawing steel wire, it is found that the heavy-duty-drawing steel wire produced using Nippon Steel's wire rod barely shows
similar fish scale crack defects. On-site inspection of the wire rods of Nippon Steel revealed that the wire rods produced using Nippon Steel had no surface damage similar to that of domestically produced wire rods.

Fig.6 Thickness of surface oxidized scale of different wire rods

The differences shown in Figure 6 were found by using a scanning electron microscope to compare and analyze the surface scale of the wire rod produced using Nippon Steel and domestic material. As shown in Fig. 6(a), the scale thickness of wire rod produced using Nippon Steel is close to 25μm, while the counterpart of the domestic material is only about 8μm as shown in Fig. 6(b). The scale on the surface of the wire rod plays a role in protecting the steel substrate of the wire rod during transportation and shoveling, so that the base of the wire rod of Nippon Steel does not suffer obvious mechanical damage under the same conditions. Therefore, technical exchange with domestic wire rod suppliers to level the scale on the wire rod surface up to close to that of Nippon Steel is one of the effective methods to reduce the defects of drawing martensite.

4. Conclusions and Comprehensive precautions

1) Of the wire rod is mechanically damaged before drawing, resulting in the lubrication failure during the drawing process, and subsequent hard friction leading to the instant temperature rising and quenching responsible for the generation of drawing martensite, and the surface martensite is snapped during the subsequent drawing, leading to the eventual crack generation.

2) Increasing the scale thickness of the wire rod, avoiding the hard friction and collision among the wire rods and the contact parts, are effective ways to prevent the fish scale cracks in the heavy-duty-drawing steel wire.

3) The measures to avoid fish scale cracks on the steel wire surface are as follows: Ameliorate the technical exchanges with suppliers and improve wire rod production process. It is then expected that the scale thickness on the surface of domestic wire rods can be close to that of Nippon Steel, so as to protect the wire rod steel substrate more effectively; Reach a negotiation with the wire rod supplier that the wire rod is packed in nylon bags before transportation, and take protective measures during the transportation; After the wire rod arrives at the factory, slowly lift and unload the wire rod to avoid mechanical damage on the wire rod surface; Install nylon plastic protection device on the forklift shaft to avoid direct impact of the shaft with the wire rod; Before releasing the C-type hook, check whether the groove exists on the surface of the C-type hook according to the operation instructions. If it does, carry out the replace and repair operations in time, and apply paraffin wax as required to prevent hard friction between the wire rod and the C-type hook; Periodically check the dephosphorization wheel, wire-borrow wheel and other
parts that may cause hard friction with the steel wire on the base of every shift, and replace or repair the abnormal parts in time.

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