Experimental Research on Influencing Factors of Basic Mechanical Properties of Stainless Steel Wire

Li Qingfu¹ a, Xu Kaiguang¹ b, Wang Yuanxiao² c and Zhang Haiwei¹ d

¹School of Water Conservancy and Environment Engineering Zhengzhou University, Zhengzhou, China
²Zhengzhou Airport and Port Investment Group Co., LTD, Zhengzhou, China
³lqflch@zzu.edu.cn, b xkgfamily@163.com, c 875157557@qq.com, d 735911317@qq.com

Abstract. The effects of drawing process, heat treatment temperature and drawing rate on the basic mechanical properties of stainless steel wire were studied by room temperature tensile test. Results indicated that with the increase of drawing passes, the tensile strength and the yield strength of stainless steel wire increased gradually and the elongation after fracture decreased gradually. With the increase of heat treatment temperature, the tensile strength decreased and the elongation after fracture increased gradually. Under the same heat treatment temperature, the tensile strength of the specimens treated by the two-drawing process was greater than that of those treated by the one-drawing process, while the elongation after fracture was less than that of those treated by the one-drawing process. The increase in drawing rate would increase the strength and modulus of elasticity of the stainless steel wire.

1. Introduction
Cable-stayed bridges and suspension bridges with cables as the main load component have become the most widely used bridge types in the world's long-span bridges because of the advantages of light weight, good stress conditions, and material saving. High-strength steel wires and strands are usually used as the cables for these two types of bridges. The cables life provided by the manufacturer is usually 20-30 years [1]. However, due to the long-term high-stress working conditions and the impact of environment, the service life of most cables is less than 15 years, but the service life of highway bridges and culverts specified in the “General Specification for Design of Highway Bridges and Culverts” is generally 100 years [2]. Based on this, it is inferred that the number of cables exchanges for these bridges during the design reference period will reach at least 6 times, significantly increasing the capital investment in the bridge life cycle.

For this reason, domestic and foreign scholars have conducted extensive research on cable durability and expected to effectively improve the service life of cables. Yao Guowen, Liu Chaochao, et al. [3] studied the mechanism of corrosion damage in acid-rain and load coupled pull-down cables. Keita Suzumura [4] studied the environmental factors affecting the corrosion of steel strands in bridges, and believed that the increase of NaCl concentration and temperature would accelerate the corrosion of galvanized steel strands. Lan Chengming, Ren Denglui, et al. [5] proposed a fatigue life estimation method for cables based on order statistics. Some other scholars proposed to improve the steel wires or steel strands, such as Zhang Jianan, Jiang Licai [1,6,7] conducted a study on the corrosion of high-strength galvanized steel wires for bridge cables. Li Chengchang, Wang Huimian, et
al. [8,9] conducted research and development of high-strength stainless steel wires for bridge cables. Currently, the production technology of stainless steel wire has been greatly developed, and related engineering applications are gradually increasing, but the relevant research on the basic mechanical properties of stainless steel wires is still relatively weak. This paper hence will study the basic mechanical properties of stainless steel wire based on the summary of the factors, and provide experimental data support for the application of stainless steel wire in bridge cables and other projects.

2. Factors affecting the mechanical properties of stainless steel wire
As a kind of metal wire, stainless steel wire has many factors affecting its mechanical properties. For example, during the processing of metal materials, the dislocation density of the crystal in the material will increase significantly as the drawing times increase, and the resistance of dislocation movement will increase, and eventually causing work hardening [10,11]. Heat treatment also affects the mechanical properties of stainless steel wire, because after heat treatment, crystal defects such as crystal dislocation and microholes make the strength and elastic modulus decrease more obviously under elevated temperature and load [12,13]. In addition, in the room temperature tensile test of metal materials, the tensile rate will also have a regular effect on the test results [14]. Therefore, this paper will study the influence of the factors such as drawing pass, surface reduction rate, heat treatment temperature and tensile rate on the mechanical properties of stainless steel wire.

3. The effect of drawing pass and surface reduction rate
3.1. Test material and number
The test materials were made of stainless steel wire rods produced by a steel mill. After drawing and straightening, the finished wires with different target diameters were obtained. The stainless steel wires were classified according to different drawing passes and surface reduction rates. The specimens of one-drawing process were directly processed from a diameter of 6.5 mm to a target diameter of 5.5 mm. The two sets of specimens that have been drawn twice were processed to the middle diameter of 6.1 mm and 5.8 mm respectively, and then processed to the target diameter. The three-drawing specimens pass through two middle diameters of 6.0 mm and 5.7 mm, and were finally processed to the target diameter. The specific grouping situation is shown in Table 1.

| order number | drawing process [mm] | surface reduction rate [%] | serial number |
|--------------|----------------------|---------------------------|--------------|
| 1            | φ=6.5→φ=5.5          | 28.4                      | 1-1-1        |
| 2            | φ=6.5→φ=6.1→φ=5.5    | 11.9→18.7                 | 1-2-1        |
| 3            | φ=6.5→φ=5.8→φ=5.5    | 20.4→10.1                 | 1-2-2        |
| 4            | φ=6.5→φ=6.0→φ=5.7→φ=5.5 | 14.8→9.8→6.9         | 1-3-1        |

3.2. Test results
According to “Metallic materials—Tensile testing—Part 1:Method of test at room temperature” [15], the stainless steel wire tensile test was carried out according to the serial number. Each of the numbers was subjected to 5 parallel tests. The mechanical properties of the stainless steel wire were tested with 5 sets of parallel tests. The average of these 5 groups of parallel test results was used as the test result of the mechanical properties of the numbered specimens. The effect of different drawing passes and surface reduction rates on tensile strength, elongation after fracture, and elastic modulus are shown in Figure 1.
Figure 1. Test value of stainless steel wire mechanical properties.

As can be seen from Figure 1., with the increase in the number of drawing passes, the tensile strength and yield strength of the stainless steel wire show an increasing trend, and the elongation after fracture shows a decreasing trend. It can be found from Figure 1. that as the number of drawing passes increases, both the tensile strength and the yield strength of the stainless steel wire tend to increase, and the elongation after breaking shows a decreasing trend. Among them, the two sets of specimens numbered 1-2-1 and numbered 1-2-2 drawn twice had little difference in elongation after fracture. The elastic modulus of the specimens increases first and then decreases with the increase in the number of drawing passes, and reaches the maximum after the second drawing. In addition the elastic modulus of the two sets of samples numbered 1-2-1 and numbered 1-2-2 are almost equal. In summary, if the target diameter is the same, the elongation and elastic modulus of the specimens after two drawing processes are not affected by the middle diameter. The middle diameter will have a significant effect on the tensile strength and yield strength of the finished stainless steel wire. And the smaller the middle diameter is, the greater the strength of the finished stainless steel wire will be.

4. The effect of heat treatment on mechanical properties

4.1. Test material and number
The test materials were made of stainless steel wire rods produced by a steel mill. After being processed to obtain the target diameter, the wires were heat-treated at different temperatures for 1 hour, and then cooled by water to obtain finished stainless steel wires. 5 sets of tests were performed under
each drawing process: stainless steel wires heat-treated at 4 different temperatures and unheat-treated ones. The specific grouping situation is shown in Table 2.

Table 2. Table of specimens grouping.

| order number | drawing process [mm] | heat treatment temperature [°C] | serial number |
|--------------|----------------------|---------------------------------|---------------|
| 1            | φ=6.5→φ=5.5          | annealed 380                     | 1-380°C       |
|              |                      | annealed 430                     | 1-430°C       |
|              |                      | annealed 480                     | 1-480°C       |
|              |                      | annealed 540                     | 1-540°C       |
| 2            | φ=6.5→φ=5.8→φ=5.5    | unannealed 380                   | 2-380°C       |
|              |                      | unannealed 430                   | 2-430°C       |
|              |                      | unannealed 480                   | 2-480°C       |
|              |                      | unannealed 540                   | 2-540°C       |

4.2. Test results
The room temperature tensile test was carried out according to “Metallic materials—Tensile testing—Part 1: Method of test at room temperature”[15]. 6 sets of parallel tests were performed for each serial number, and then the tensile strength, elongation after fracture were measured. The average of 6 parallel tests results was taken as the test result. The change trends of the tensile strength and elongation after fracture with the heat treatment temperature in each group are shown in Figure 2. to Figure 3.

(a) tensile strength
(b) elongation after fracture

Figure 2. Test results of one-drawing process specimens.
Figure 2. and Figure 3. show that under the same drawing process, the tensile strength of the specimens heat-treated at different temperatures gradually decreases with the increase of the heat treatment temperature, but is higher than that of the unheat-treated specimens. The elongation after fracture gradually increases with the increase of the heat treatment temperature, but is smaller than that of the specimens without heat treatment. Comparing Figure 2. with Figure 3., it can be seen that at the same heat treatment temperature, the tensile strength and elongation after fracture of the specimens treated by different drawing processes are obviously different. Specifically, the tensile strength of the two-drawing specimens is obviously higher than that one-drawing at the same heat treatment temperature. The elongation after fracture of two-drawing specimens is much less than one-drawing specimen. In addition, the tensile strength and elongation after fracture of the specimens under different drawing processes have the same tendency as the heat treatment temperature increases. This shows that the difference in the drawing process will only change the tensile strength and elongation after fracture of the specimens without changing the variation with the heat treatment temperature.

5. The effect of tensile rate on mechanical properties of stainless steel wire

5.1. Test material and number
The stainless steel wires produced by a steel mill were used to test the effect of the tensile rate on the mechanical properties of the stainless steel wire according to the “Metallic materials—Tensile testing—Part 1: Method of test at room temperature”[15]. According to the different drawing rates, the specimens were divided into 3mm/min(v1) and 5mm/min(v2) categories. At the same time, considering the different processing technologies, each category was divided into 7 groups. The solution-treated specimens were represented by the letter G, and the untreated ones were represented by the letter W. The specific grouping and numbering are shown in Table 3.

| order number | drawing process [mm] | tensile rate [mm/min] | serial number |
|--------------|----------------------|-----------------------|---------------|
| 1            | 5.5mm stainless steel wire rod | 3 | 5.5-G-v1 |
| 2            | φ=6.5→φ=4.85         | 3 | 4.85-G- v1 |
| 3            | φ=6.5→φ=4.75         | 3 | 4.75-G- v1 |
| 4            | φ=6.5→φ=4.65         | 3 | 4.65-G- v1 |
| 5            | φ=6.5→φ=4.85         | 3 | 4.85-W- v1 |
| 6            | φ=6.5→φ=4.75         | 3 | 4.75-W- v1 |
| 7            | φ=6.5→φ=4.65         | 3 | 4.65-W- v1 |
| 8            | 5.5mm stainless steel wire rod | 5 | 5.5-G-v2 |

(a) tensile strength  
(b) elongation after fracture
5.2. Test results
The tensile strength, yield strength, elongation after fracture, and elastic modulus of the 14 specimens in Table 3 were measured at room temperature. In each group of specimens, 10 parallel tests were performed. The average of 10 parallel test results was taken as the test result. The histogram of the test results is shown in Figure 4.

### Table 3

| Specimen | Tensile Strength/MPa | Yield Strength/MPa | Elastic Modulus/MPa | Elongation After Fracture/% |
|----------|----------------------|--------------------|---------------------|-----------------------------|
| 9        | 6.5→4.85             | 5                  | 4.85-G              | v2                          |
| 10       | 6.5→4.75             | 5                  | 4.75-G              | v2                          |
| 11       | 6.5→4.65             | 5                  | 4.65-G              | v2                          |
| 12       | 6.5→4.85             | 5                  | 4.85-W              | v2                          |
| 13       | 6.5→4.75             | 5                  | 4.75-W              | v2                          |
| 14       | 6.5→4.65             | 5                  | 4.65-W              | v2                          |

In the 7 groups of specimens, the tensile strength and yield strength of 6 groups of specimens at the tensile rate of 5mm/min are greater than that at the tensile rate of 3mm/min. And the elastic modulus of 6 groups of specimens at the tensile rate of 5mm/min is greater than that at the tensile rate of 3mm/min. It can be seen that the increase of the tensile rate will bring about a significant increase in the tensile strength, yield strength, and elastic modulus of the stainless steel wire, but it does not cause a significant regular effect on the elongation after fracture of the stainless steel wire.

6. Conclusions
Through the series of room temperature tensile test on stainless steel wire, the following conclusions can be drawn:

- **(c) elongation after fracture**
- **(d) elastic modulus**

Figure 4. Effect of tensile rate on mechanical properties of stainless steel wire.
(1) The increase of drawing passes could increase the tensile strength and yield strength of stainless steel wire, and reduce its elongation after fracture.

(2) If the target diameter was the same for multiple drawn stainless steel wire specimens, the smaller the intermediate diameter was, the higher the strength of the finished stainless steel wire would be, and the elongation after fracture was insensitive to the size of the intermediate diameter.

(3) The tensile strength of stainless steel wire could be significantly reduced by heat treatment, and the tensile strength decreased with the increase of heat treatment temperature, and the elongation after fracture increased with the increase of heat treatment temperature.

(4) The tensile strength and yield strength of stainless steel wire would increase with the increase of the tensile rate, and the elongation after fracture was insensitive to the change of the tensile rate.

As a new type of corrosion resistant material, stainless steel wire will be more and more widely used in practical engineering with the improvement of production technology and the reduction of cost. However, due to the limited number of tests, the conclusions are only for reference of engineering application.

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