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Strengthening mechanism and yield strength prediction of cold-drawn commercially pure aluminum wire

Rui. Li[1], Jiapeng Hou[2], Wenhao Yang[3], Hongyun Yu[1], Qiang. Wang[2,*], Zhefeng Zhang[2]

[1]National Quality Supervision & Inspection Center of Electrical Equipment Safety Performance, Zhejiang Huadian Equipment Testing Institute, Hangzhou 310015, PR China;

[2]Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, 72 Wenhua Road, Shenyang 110016, PR China.

[3]Dept. of Mechanical Engineering Tsinghua University, Beijing100000, PR China.

Abstract. Commercially pure aluminum is a widely used conductive material in the field of overhead transmission. Yield strength, which is closely related to the reliability of conductive material in service, is an important parameter of mechanical property. Aluminum wire, which is widely used as the outer layer of steel core aluminum strand, is usually prepared by cold-drawing process. With the increase of area reduction, the strength of aluminum wire increases continuously and thus yield strength prediction becomes a very important scientific issue based on the strengthening mechanism analysis. In this paper, the contributions of grain refinement and hard texture to the yield strength were calculated by characterizing the microstructure of aluminum wire with different area reductions. Subsequently, the yield strength prediction model was set up by means of the quantitative calculation and function fitting of grain refinement strengthening and texture strengthening. By using this model, the yield strength of aluminum wire can be well predicted based on the average grain size of initial aluminum rod and this model can also guide the design and production of aluminum wire in industry field.

1. Introduction

With the rapid development of economy, the national electricity consumption is increasing year by year. However, the distance from the power plant to the power terminal requires is very long and thus the long distance transmission of power is inevitable. Overhead wire is an important carrier for transmitting electric energy from the generating end to the receiving end. In traditional structural metal materials, aluminum is the most suitable material for conductors due to its high specific strength, low cost, good mechanical and high electrical conductivity, so it has been widely applied in the field of overhead transmission lines [1, 2]. In particular, commercially pure aluminum is widely used as overhead conductor. For example, the outer layers of aluminum conductor steel reinforced (ACSR) and aluminum conductor alloy reinforced (ACAR) are commonly composed of commercially pure aluminum wire [3-5].

As a component of overhead transmission line, the aluminum wire needs to bear some loads, such as wind load and dead weight in service, and therefore the yield strength, which directly determines the safety and reliability, is an important parameter to evaluate the performance of aluminum wire

[6-9]. Commercially pure aluminum wire is usually made by the pure aluminum rod after multiple passes in the cold-drawn preparation. The final yield strength of aluminum wire is closely related to the product's qualification as well as some other properties. Consequently, the prediction of yield strength has already become a very important scientific issue. The yield strength prediction of aluminum wire with different area reductions based on the characterization of the initial aluminum rod can avoid some tedious process flow for obtaining the yield strength of aluminum wire, such as multiple could-drawn passes and tests. In previous study, Hou etc. report that with the increase of area reduction, the yield strength of aluminum wire increase continuously, which can be attributed to the grain refinement and texture evolution. It was found that although researchers have studied the microstructure evolution and strengthening mechanism of aluminum conductor in cold drawing process, few literature reports the yield strength prediction of aluminum wire as conductive material.

In this paper, the relation between the yield strength and the area reduction was set up combined microstructure characterization and strengthening mechanism analysis. Finally, a model of yield strength prediction was established, which can predict the yield strength of aluminum wire with different area reductions only based on the average grain size of initial aluminum rod. The research result has important theoretical guiding significance for the mechanical performance design and the process design of the commercially pure aluminum wire.

2. Experimental procedure

2.1 Materials and process

Material used in this investigation was A6 aluminum. The chemical composition is as follows(wt.%): Si 0.11, Fe 0.25, Cu 0.01, others 0.03, Al 99.6. Commercially pure aluminum wires with different area reductions were prepared by the cold-drawing of the initial aluminum rod with the diameter of 9.5 mm. Area reduction is a parameter of deformation, which can be calculated by the following equation:

$$\varepsilon = \left(1 - \frac{A_i}{A_0}\right) \cdot 100\% \quad (1)$$

Where, ε, deformation; A_i, the cross-sectional area of aluminum wire after i_{th}-pass cold-drawn treatment; A_0, the cross-sectional area of initial aluminum rod.

2.2 Microstructure characterization

Samples with the thickness of 1.0mm were cut along the axial direction from the commercially pure aluminum wire for microstructure characterization. First, samples were polished by SiC papers from 400# to 2000#. Afterward the samples were electrolytic-polished in the electrolytes, which contains perchloric acid (analytical purity, 10% in volume) and alcohol (analytical purity, 90% in volume) at 0°C for 10s. The grain size and grain orientation of aluminum wire were analyzed by Electron Back-Scattered Diffraction (EBSD), which is integrated in the ZEISS SUPRA 35 scanning electron microscope (SEM).

Samples for TEM observation were also cut along the axial direction. First, the samples were grinded to ~0.05mm by SiC papers and then double electrolytic ion thinning were conducted in the electrolytes containing perchloric acid (analytical purity, 20% in volume) and methanol (analytical purity, 80% in volume) at 20°C for 10s. Finally, the samples were characterized by FEI Tecnai F20 TEM at the voltage of 200 kV.

2.3 Mechanical properties test

Three samples with the length of 200mm were prepared under each area reduction. Tensile tests were carried out on an INSTRON 5982 static tensile test machine. The loading direction is parallel to the axial direction of aluminum wire with a strain rate of 1.0×10^{-3} s^{-1}.

3. Results and discussion

3.1 Microstructure evolution

In figure 1a-c, with the increase of area reduction, grains are obviously elongated along the axial direction according to the TEM observations. Moreover, a very small number of dislocations can be observed in the grains, which can be attributed to the high level of fault energy causing the cross-slip of dislocations during the deformation and leading to the recovery of dislocations [10-13].

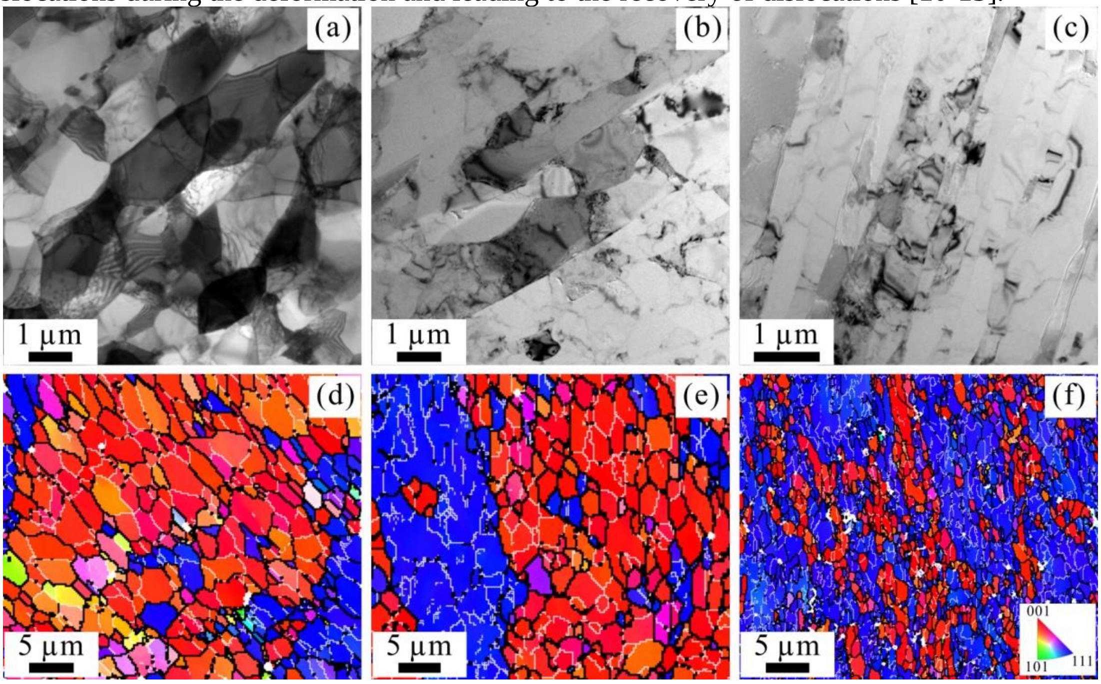

Figure 1 (a-c) TEM observation of commercially pure aluminum wire with the area reductions of 0%, 24.6% and 90.2%; (d-f) EBSD maps of commercially pure aluminum wire with the area reductions of 0%, 24.6% and 90.2%, scanning in the radial direction.

The microstructures of the aluminum wires with different area reductions were characterized by EBSD as shown in figure 1d-f. The results show that most of grains are equiaxed observed from the radial direction, and with the increase of deformation, the grain size is decreasing. In addition, it can be seen from the orientation distribution that there are two orientations, i.e., <001> and <111>, for the grains on the cross-sectinal area of aluminum wire. In the initial aluminum rod, most grains are of <001> orientations. However, with the increase of deformation, the grains with <001> orientations are decreasing, and meanwhile the grains with <111> orientations increase obviously. It means that the grains with <001> orientations are gradually transformed into the grains with <111> orientations. That is to say, at the very beginning <001> texture is the main texture and <111> texture is gradually enhanced with the increase of drawing deformation.

The volume fractions of <001> texture and <111> texture were calculated combined the EBSD maps and equation (2) as shown in figure 2. With the increase of deformation, the volume fraction of <111> texture is enhanced from 9.8% to 76.0%, and correspondingly the volume fraction of <001> texture drops from 90.2% to 24.0%.

$$f_{<iii>} = \frac{S_{<iii>}}{S_0}, \qquad (2)$$

Where, $f_{<iii>}$ is the volume fraction of <iii>texture; $S_{<iii>}$ is the area of grains with <iii>orientation; S_0 is the total area of statistics.

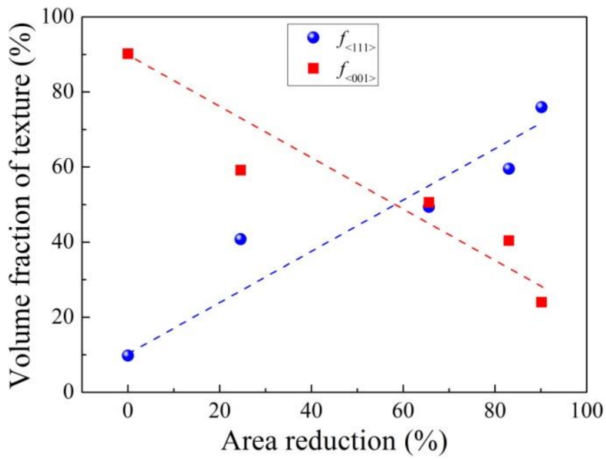

Figure 2 Statistical volume fraction of texture in the commercially pure aluminum wire with different area reductions.

3.2 Strengthening mechanism analysis

For the aluminum wires with different area reductions, it is assumed that the strengthening mechanisms are independent of each other in the process of yield strength improvement, and then the yield strength of metal with texture can be described by the following equation [1, 14]:

$$\sigma_{YS} = \sigma_0 + \sigma_g + \sigma_d + \sigma_{ss} + \sigma_p + \sigma_t \,, \tag{3}$$

Where, σ_0 is the Peierls stress; σ_{HP} is the contribution of grain boundary strengthening; σ_d is the contribution of dislocation strengthening; σ_{ss} is the contribution of solid solution strengthening; σ_p is the contribution of precipitation strengthening; σ_t is the contribution of texture strengthening.

For the commercially pure aluminum wire containing little impurity elements, solid solution strengthening and precipitation strengthening need not to be considered. Moreover, there are only a very small number dislocations existing in the aluminum wire, so dislocation strengthening can also be ignored. The yield strength of aluminum wire can be expressed as follows:

$$\sigma_{YS} = \sigma_{HP} + \sigma_t \,. \tag{4}$$

In figure 1, the orientation maps show that only two kinds of textures, <001> texture and <111> texture, exist in the aluminum wire after cold-drawn deformation.

Therefore, the yield strength caused by texture evolution can be defined as the sum of the contributions of the <001> texture and the <111> texture. And thus the total yield strength of aluminum wire caused by texture evolution can be expressed as follows:

$$\sigma_{YS} = f_{<001>} \cdot \sigma_{<001>} + f_{<111>} \cdot \sigma_{<111>} \,, \tag{5}$$

Where, $f_{<001>}$ and $f_{<111>}$ are the volume fractions of <001> texture and <111> texture, respectively; $\sigma_{<001>}$ and $\sigma_{<111>}$ represent the contributions of the grains with <001> orientation and <111> orientation, respectively.

According to the Schmidt's law, the saturated shear stress of <001> orientations and <111> orientations ($\tau_{<001>}$ and $\tau_{<111>}$) can be calculated by the following equation:

$$\tau_{<001>} = \sigma_{<001>} \cdot \Omega_{<001>} \,, \tag{6}$$

$$\tau_{<111>} = \sigma_{<111>} \cdot \Omega_{<111>} \,, \tag{7}$$

Where, $\Omega_{<001>}$ (0.408) and $\Omega_{<111>}$ (0.272) represent the Schmidt's factor of <001> orientation and <111> orientation, respectively.

For the polycrystalline aluminum wire, the critical saturated shear stress of <001> orientation is equal to that of <001> orientation. Therefore, equation (6) and equation (7) are substituted into equation (5), and the following equation can be obtained:

$$\sigma_{YS} = \tau_{<001>} \cdot \frac{f_{<001>}}{\Omega_{<001>}} + \tau_{<111>} \cdot \frac{f_{<111>}}{\Omega_{<111>}}$$
$$= \tau_{HP} \cdot \left(\frac{f_{<001>}}{\Omega_{<001>}} + \frac{f_{<111>}}{\Omega_{<111>}}\right). \tag{8}$$

Here, a parameter is defined, i.e., orientation factor [15-18] :

$$M_S = \frac{f_{<001>}}{\Omega_{<001>}} + \frac{f_{<111>}}{\Omega_{<111>}}. \tag{9}$$

The critical saturated shear stress of aluminum wire (τ_{HP}) can be calculated by the following equation:

$$\tau_{HP} = \frac{\sigma_{HP}}{M_0}, \tag{10}$$

Where, $M_0 = 3.06$ is the orientation factor of polycrystalline pure aluminum without texture.

Substituting the equation (9) and the equation (10) into the equation (8):

$$\sigma_{YS} = \sigma_{HP} \cdot \frac{M_S}{M_0}. \tag{11}$$

According to the equation (4) and the equation (11), the strength increment caused by the texture evolution in the aluminum wire can be expressed as:

$$\sigma_t = \sigma_{YS} - \sigma_{HP}$$
$$= \sigma_{YS} \cdot \left(1 - \frac{M_0}{M_S}\right). \tag{12}$$

Finally, the strengthening effects caused by texture strengthening and grain refinement strengthening can be obtained by calculation.

The grain sizes of aluminum wires with the area reductions of 0, 24.6%, 65.6%, 83.1% and 90.2% were statistically observed as well as the volume fractions of <001> texture and <111> texture. Hereby, the orientation factor is calculated based on the above results, the strength increments from texture strengthening and grain refinement strengthening. All the calculation results are listed in table 1.

Table 1. Texture volume fraction, radial grain size and orientation factor of commercially pure aluminum wire with different area reductions as well as the strength increment caused by grain refinement strengthening and texture strengthening.

Area reduction (%)	0	24.6	65.6	83.1	90.2
$f_{<001>}$ (%)	90.2	59.2	50.6	40.4	24.0
$f_{<111>}$ (%)	9.8	40.8	49.4	59.6	76.0
d (μm)	1.60	0.83	0.77	0.59	0.40
M_S	2.57	2.95	3.06	3.18	3.38
σ_{HP} (MPa)	107.1	124.7	144.8	159.8	175.9
σ_t (MPa)	-17.1	-4.4	-0.2	6.3	18.5
σ_{YS} (MPa)	90.0	120.4	144.7	166.1	194.4

3.3 Yield strength prediction model

The yield strength of metal is an important mechanical performance parameter, and it is also a common mechanical performance parameter for engineering design. Yield usually represents the initial plastic deformation resistance of metal, and for polycrystalline metals, yield strength usually represents the plastic deformation resistance of all grains. In essence, the yield of metal is the result of dislocation multiplication and movement. In the commercially pure aluminum wire, the dimension, shape and orientation of grains greatly influence the dislocation multiplication and movement. After the grain refinement, the moving distance between the dislocation and the grain boundary is reduced, and therefore the deformation resistance of metal can be improved. Texture represents the crystal orientation of most grains, and different crystal orientations also have significant influences on the dislocation movement. Therefore, the yield strength of aluminum wire mainly consisted of grain refinement strengthening effect and texture strengthening effect as expressed in equation (4).

Actually, for commercially pure aluminum wire, the size, shape and dimension of grains are all influenced by the plastic deformation. With the increase of area reduction, the dimension of grain measured on the radial direction is gradually decreasing. The hindrance of grain boundary to the dislocation movement is constantly enhanced, and its deformation resistance is increasing continuously. In addition, the larger the deformation, the smaller is the diameter of aluminum wire. Under the influence of circumferential stress and axial tensile stress, the grain inclines to change from <001> orientation to <111> orientation gradually, which has great contribution to the deformation resistance. Therefore, the strength of commercially pure aluminum wire is closely related to the drawing deformation, and essentially it is influenced by grain size, grain shape and grain orientation. The premise of establishing the relation between the strength and the deformation is to establish the relation between the volume fraction of texture and the deformation degree (texture strengthening-deformation relation), and the relation between the average radial grain size and the deformation degree (grain refinement strengthening-deformation relation).

The variation of the volume fraction of texture with area reduction is shown in figure 3(a). With the increase of area reduction, the volume fraction of texture presents two parabolic relations. Meanwhile, the contribution of <111> texture to the yield strength of aluminum wire is linear, which follows the mixture law. Essentially, texture strengthening can be attributed to the anisotropy of mechanical properties for crystals. As a result, the relation between the texture strengthening effect and the area reduction is parabolic, which can be fitted by the following equation:

$$\sigma_t = a_1 + b_1 \cdot \varepsilon^2 \tag{13}$$

The fitting curve is shown in figure 3 a-b, getting a_1=-18.0 MPa, b_1=4.0×10^{-3} MPa.

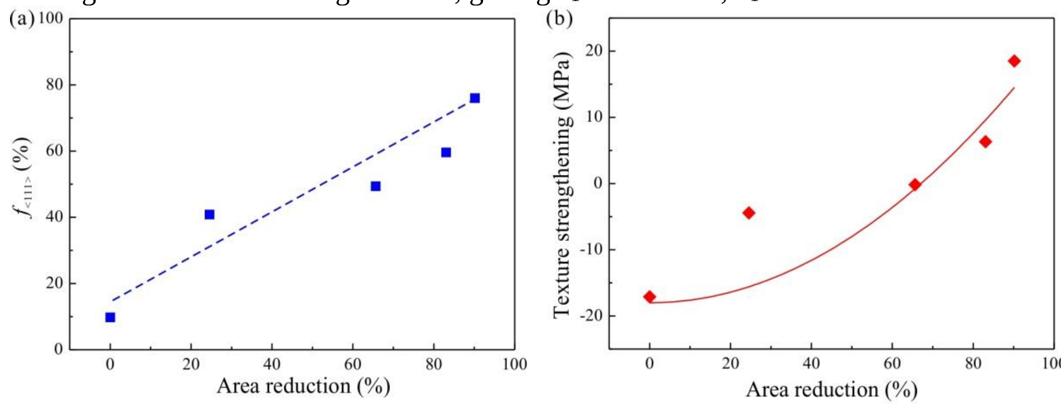

Figure 3 For the commercially pure aluminum wire, (a) relation between the volume fraction of <111> texture and the area reduction; (b) relation between the texture strengthening and the area reduction.

Grain refinement leads to the introduction of a large number of grain boundaries in the unit volume. Therefore, the distance between the dislocation and the grain boundary decreases when the dislocation moves in the grain, which may significantly enhance the resistance of dislocation movement.

During the area reduction, the average grain size on the radial section decreases continuously. Actually, the volume of grain usually keeps the same during the drawing deformation, but the shape of grain changes obviously towards elongation. On the radial section, the sizes of grains are decreasing, which play an important role as grain refinement strengthening.

According to the materials theory, grain refinement strengthening can be expressed by Hall-Petch relation [19-21]:

$$\sigma_{HP} = \sigma_0 + k \cdot d^{-1/2} \tag{14}$$

By the curve fitting, it can be obtained that: $\sigma_0 = 34.57MPa$, $k = 91.26MPa \cdot \mu m^{1/2}$.

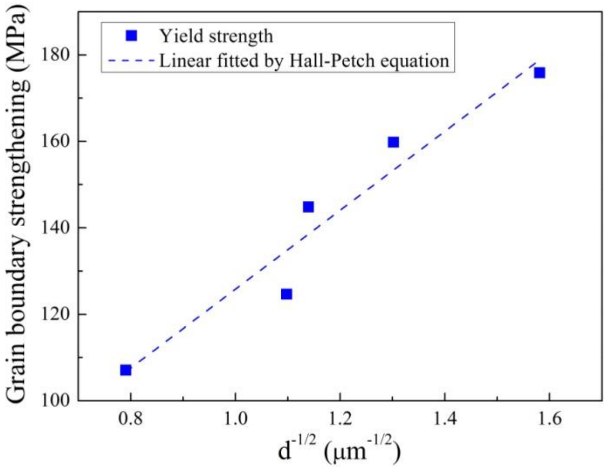

Figure 4 Fitting curve of grain boundary strengthening in commercially pure aluminum wire with different area reductions by Hall-Petch equation.

In the drawing process of commercially pure aluminum wire, the size of grain is directly related to the area reduction, because the stress state of wire is mainly based on circumferential compressive stress and axial tensile stress. It lays the foundation for establishing the relation between the average grain size and the deformation of aluminum wire. The relation between the grain refinement strengthening and the area reduction was set up based on the relation between the grain size and the area reduction.

In the above words, area reduction is the ratio of radial area during the drawing process. Ideally, aluminum wire is composed of only one grain, and the area is the cross-sectional area of the single grain. Therefore, the area reduction is proportional to the square of grain diameter. In the case of polycrystalline, the radial grain size is proportional to the diameter of the aluminum wire, and the relationship between the radial grain size and the area reduction can be derived as follows:

$$d_i = (1 - 0.01 \cdot \varepsilon_i)^{1/2} \cdot d_0 \tag{15}$$

Where, d_i is the radial grain size at the area reduction of ε_i; d_0 is the grain size of initial aluminum rod.

In figure 5, the radial grain size obtained by the equation (15) is in good agreement with the measured radial grain size. It indicates that the relation between the size of the radial grain and the area reduction described by the above equation is relatively accurate.

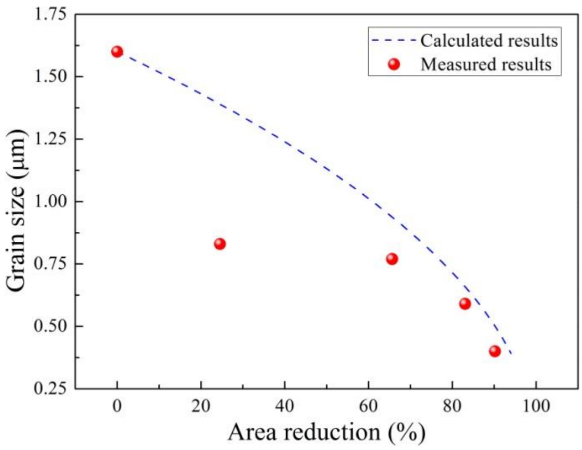

Figure 5 Relation between the radial grain size and the area reduction.

Substituting the equation (15) into equation (14):

$$\sigma_{HP} = \sigma_0 + k \cdot d^{-1/2} = \sigma_0 + k \cdot \left[(1 - 0.01 \cdot \varepsilon_i)^{1/2} \cdot d_0\right]^{-1/2} \tag{16}$$

Substituting the equation (16) and (13) into equation (4):

$$\begin{aligned}\sigma_{UTS} &= \sigma_t + \sigma_{HP} \\ &= a_1 + b_1 \cdot \varepsilon^2 + \sigma_0 + k \cdot \left[(1 - 0.01 \cdot \varepsilon)^{1/2} \cdot d_0\right]^{-1/2}\end{aligned} \tag{17}$$

Substituting the parameter obtained from the fitting of the equation (13) and (14) into equation (17), the relation between the yield strength and the area reduction can be set up as:

$$\sigma_{YS} = 16.57 + 0.004 \cdot \varepsilon^2 + 91.26163 \cdot \left[(1 - 0.01 \cdot \varepsilon)^{1/2} \cdot d_0\right]^{-1/2} \tag{18}$$

The Equation (18) can be considered as a model to predict the yield strength of aluminum wires with different area reductions on the premise of the known the average grain size of initial aluminum rod.

3.4 Yield strength prediction model verification

The actual results are compared with the results calculated from the equation (18). In this paper, two kinds of aluminum wires with the same initial grain size (1.6 μm) were chosen as the validation Data. The only difference between the two aluminum wires is the deformation path. The results show that the actual test results are in good agreement with the results calculated from the equation (18). The results also indicate that as long as the initial grain size of aluminum rod is the same, the strength is basically the same after the same deformation. That is to say, the yield strength of commercially pure aluminum wire is closely related to the grain size of initial aluminum rod and the area reduction, which has nothing to do with the deformation path. Furthermore, it is the basis for predicting the yield strength of aluminum wire.

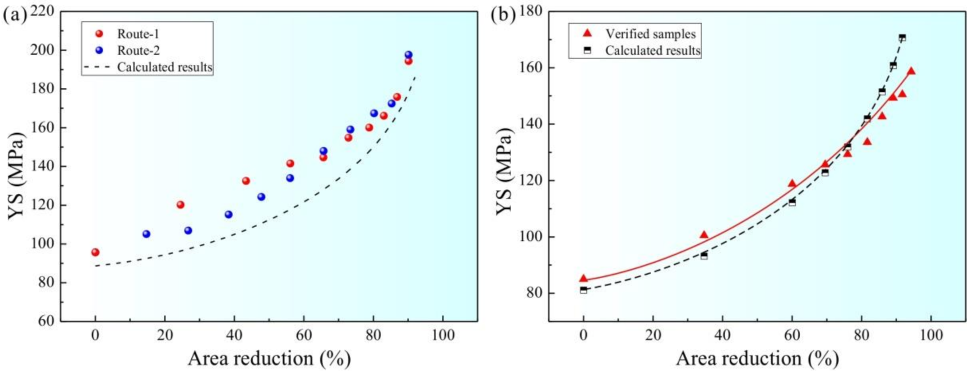

Figure 6 Comparisons between the strength obtained by theoretical calculation and the actual test.

Furthermore, another aluminum wire with the initial grain size of 2.0μm was also adopted to verify the prediction model.

Substituting the grain size, 2.0μm, into the equation (18), the yield strength can be obtained:

$$\sigma_{YS} = 16.57 + 0.004 \cdot \varepsilon^2 + 91.26163 \cdot \left[(1 - 0.01 \cdot \varepsilon)^{1/2} \cdot 2\right]^{-1/2} \tag{19}$$

As shown in figure 6 (b), the data calculated by the equation (19) are in good accordance with the actual test data, indicating that using the radial grain size of initial aluminum rod can predict the yield strength of commercially pure aluminum wire with different area reductions.

4. Conclusions

In this paper, the microstructure evolution, strengthening mechanism and yield strength prediction model of commercially pure aluminum wire with different drawing deformations were investigated based on the microstructure characterization, mechanical property tests and statistical analysis. Conclusions can be drawn as follows:

[1] With the increase of area reduction, the axial grain of aluminum wire is elongated, the radial

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grain is refined, and <001> texture is gradually transformed into <111> texture.

[2] The grain refinement on the radial section and the transformation of <001> texture to <111> texture are the main reasons for the increase of yield strength, i.e., grain refinement strengthening and texture strengthening. The contribution of grain refinement strengthening and texture strengthening to the yield strengthe of commercially pure aluminum wire is quantitatively analyzed.

[3] Based on the quantitative calculation results of grain refinement strengthening and texture strengthening as well as function fitting, a prediction model for the yield strength of commercially pure aluminum wire is proposed. Based on the radial grain size of initial aluminum rod, the yield strength of commercially pure aluminum wires with different area reductions can be predicted. In addition, the accuracy and correctness of the prediction model have also been verified by the verification experiment.

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