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Microstructure evolution and strengthening mechanisms of cold-drawn commercially pure aluminum wire

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ABSTRACT

The tensile strength of cold-drawn commercially pure aluminum wire shows an obvious three-stage characteristic, including the first strengthening stage, steady stage and second strengthening stage, with increasing extrusion strain. The dislocation density, intensity of ⟨111⟩ texture and percentage of high-angle grain boundaries are apparently increased in the second strengthening stage. Consequently, the final strengthening mechanisms may be well explained by the existence of the high-density dislocation, the ⟨111⟩ texture and high-angle grain boundary.

1. Introduction

As a structural material with good conductivity, commercially pure (CP) aluminum is widely used in power industry. For instance, the external-layer of aluminum conductor steel reinforced (ACSR) widely applied to overhead power lines is commonly made of CP aluminum [1,2]. Since this kind of CP aluminum wire (CPAW) is often achieved by a standard manufacturing route consisting of cold-drawing for different passes, studying the mechanical properties and the microstructure evolution of CPAWs during different passes of cold-drawing is significantly important. Although the extrusion strain of samples manufactured by cold-drawing in this study is not as high as those produced by the severe plastic deformation (SPD) techniques including equal-channel angular extrusion (ECAE), high-pressure torsion (HPT) and accumulated roll bonding (ARB), all of them are effective approaches to strengthen materials and fabricate ultrafine-grained or nanocrystalline materials with texture and anisotropic mechanical property [3–5]. The enhancement of strength in those materials fabricated by the various SPD techniques may be attributed to the increase of the dislocation density and the grain refinement induced by dislocation strengthening mechanism and grain-boundary strengthening mechanism, respectively [6–8]. The tensile properties of pure aluminum, copper or magnesium alloys after SPD processing show obvious differences in transverse direction (TD), normal direction (ND) and extrusion direction (ED) due to the formation of texture [9–13]. The influence of texture on the anisotropic mechanical properties of magnesium, titanium, copper and aluminum induced by ECAE has received much attention over the past decades [10,14–16]. However, the development of mechanical properties to the aluminum conductors under cold-drawing is rarely reported. In this study, the CPAWs fabricated by industrial cold-drawing for different passes were selected as the samples for tensile tests, electron backscatter diffraction (EBSD) and transmission electron microscopy (TEM) observations in order to establish the relation between the mechanical properties and the microstructure evolution. Meanwhile, the strengthening mechanisms in materials processed by different strain levels of plastic deformation techniques can be perfect. As another important property of CPAWs, the electrical conductivity will be discussed in further research.

2. Experimental

The original aluminum rod with a diameter of 9.89 mm was rolled from aluminum ingot as the object for cold-drawn processing. The chemical composition of the CP aluminum (wt%) is aluminum ≥ 99.7 and impurity ≤ 0.3. The CPAW with a diameter of 3.25 mm was manufactured by cold drawing for 9 passes from the

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original aluminum rod which was cold-drawn on a bull block drawing machine. The total area reduction is about 89.2% and the other parameters are listed in Table 1. The uniaxial tensile tests of the cold-drawn CPAWs were carried out on a Shimadzu AG-X testing machine. All the tensile specimens with a gauge length of 150 mm were tested at room temperature with a constant strain rate of $1.0 \times 10^{-3}\,s^{-1}$ and the tensile axis was parallel to the drawing direction. Some cylindrical aluminum pieces with a thickness of 1.0 mm cut from the cold-drawn CPAWs for different passes were made into specimens for EBSD observations. The samples were polished using 2000# emery papers and then electrolytically polished for ~90 s at 0 °C using an etching solution containing 10% perchloric acid and 90% alcohol in volume. The grain orientation distribution and the texture evolution were measured by the EBSD technique integrated in ZESIS SUPRA 35 scanning electron microscope (SEM). TEM samples were cut from the cross section of CPAWs, ground to a thickness of ~0.05 mm and then twin-jet electropolished using a solution of 20% perchloric acid and 80% methanol in volume. TEM foils were examined by an FEI Tecnai F20 microscope operating at 200 kV.

3. Results and discussion

Fig. 1a shows the relation between the yield strength (YS) and the extrusion strain. Apparently, the YS–extrusion strain curve exhibits three-stage characteristics remarkably, i.e., stages I, II and III, which may be defined as the first strengthening stage, steady stage and secondary strengthening stage respectively. It should be noted that the curves in Figs. 1 and 2 are only an expression for the understanding of the tendency. In stage I, the YS initially increases from 85.7 MPa to 144.8 MPa at the critical extrusion strain of 50.2%. Then the values of YS gradually become stable at ~130 MPa in stage II. However, the YS once again increases to 167.6 MPa at the end of stage III. For the ultimate tensile strength (UTS), it has the similar trend as YS with increasing extrusion strain, as shown in Fig. 1b. Since there is obvious increment in the strength when the extrusion strain is less than 50.2% and higher than 71.6%, there must be some differences in strengthening-mechanisms dominating the mechanical properties of the cold-drawn CPAWs in these two stages, which will be discussed later.

It is well known that the dislocation density increases rapidly in the early stage of plastic deformation; meanwhile, dislocations may interact with each other and hinder the movement themselves. As a result, the increase of dislocation density in the interior of grains may lead to the increment of strength [17–19]. TEM observation was employed as a qualitative analysis method to show the features of dislocation density evolution of CPAWs after cold drawing with increasing the degree of drawing strain. Fig. 2 shows that there are almost no dislocations observed in the cold-drawn CPAWs for 0 pass. For the cold-drawn CPAWs for 2nd and 5th pass, dislocations can be easily found in some grains or subgrains. Upon further straining, the dislocations appear in most of the grains of the CPAWs processed by 9-pass cold drawing. Consequently, the introduction of dislocations can be regarded as the main reason for the increase of YS and UTS in stages I and III. Compared with the stages I and II, the strengthening mechanisms in stage III should be much more significant and interesting because the extrusion strain to the CP aluminum conductors is extremely high.

It should be noted that the increment of dislocation density may be not the only strengthening mechanism for the rapid increase of YS in stage III, since grain boundaries (GBs) are also considered as an imperative factor for strengthening materials [20–22]. Therefore, the misorientation was measured and Fig. 2

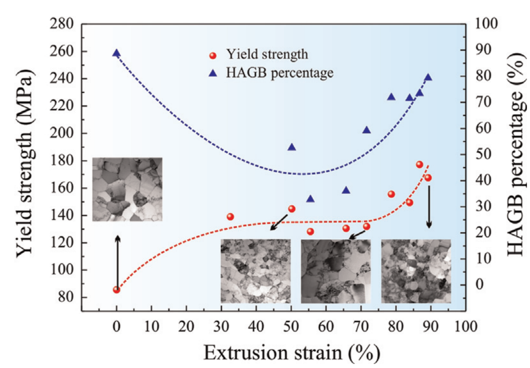

Fig. 2. YS vs. extrusion strain curve and percentage of HAGB vs. extrusion strain curve of CPAWs after cold drawing for different passes. TEM images of the CPAWs processed by cold drawing for 0, 2, 5 and 9 passes.

Table 1
Diameter and area reduction of cold-drawn CPAWs in each pass.

Pass	0	1	2	3	4	5	6	7	8	9
Diameter (mm)	9.89	8.12	6.98	6.60	5.79	5.27	4.56	3.97	3.6	3.25
Area reduction (%)	0	32.6	50.2	55.5	65.7	71.6	78.7	83.9	86.7	89.2

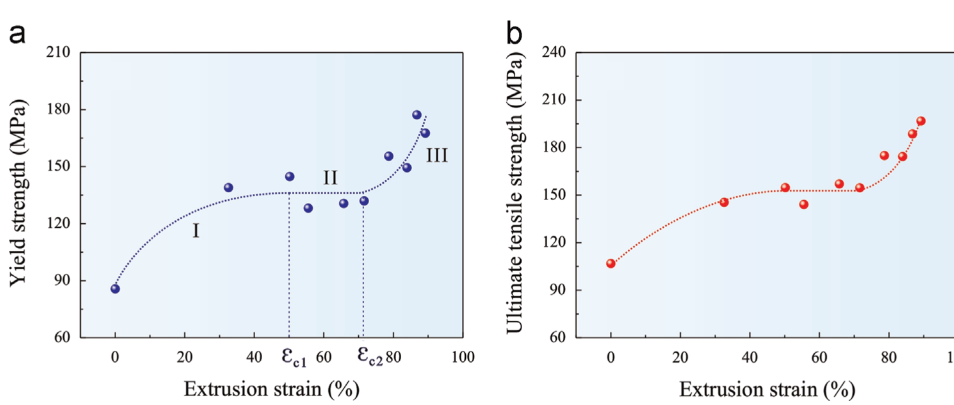

Fig. 1. Yield strength (a) and ultimate tensile strength (b) vs. extrusion strain curve for the cold-drawn CPAWs.