

Texture evolution and flow stress of columnar-grained polycrystalline copper during intense plastic deformation process at room temperature

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ABSTRACT

The texture evolution and microstructure in continuous columnar-grained (CCG) polycrystalline copper during wire drawing at room temperature were investigated quantitatively using the electron backscatter diffraction (EBSD) technique, and the stored energy and flow stress were calculated based on the texture constitution and structural parameters of different texture components measured by high resolution EBSD. The results indicate that the development of $\langle 111 \rangle$ texture within original $\langle 100 \rangle$ columnar grains was significantly slower compared with that in equiaxed polycrystalline copper, e.g. the volumetric ratio of the $\langle 111 \rangle$ to $\langle 100 \rangle$ component in columnar-grain copper was 0.82 at the strain of 2.98, while it was 2.96 in equiaxed polycrystalline copper at the same strain. The relatively low content of $\langle 111 \rangle$ fiber texture accounted for the low flow stress, low work hardening rate and excellent cold plastic extensibility of the columnar-grained polycrystalline copper. The average size of the dislocation cells developed within the $\langle 111 \rangle$ fiber was the minimum among all the deformation texture components, and decreased rapidly with the increase of strain, leading to a high stored energy, a high flow stress and a high work hardening rate. On the other hand, the average size of the dislocation cells developed within the $\langle 100 \rangle$ fiber was the maximum, which held a large value at high strain, leading to a low stored energy, a low flow stress and a low work hardening rate.

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1. Introduction

Continuous columnar-grained (CCG) polycrystalline copper wires produced by continuous unidirectional solidification (CUS) possess excellent plastic extensibility at room temperature. For example, a 19.7 μm -diameter ultra-fine wire could be obtained from a 17.0 mm-diameter CCG copper rod by wire-rolling and drawing at room temperature without any intermediate softening heat treatment with a total elongation up to $7.4 \times 10^7\%$ and a true strain of 13.5 [1]. Meanwhile, a high electrical conductivity of 97.6% IACS also maintained at the strain of 11.12. The extreme extensibility of CCG copper makes an annealing-free fabrication of superfine wires feasible and may reduce the manufacture cost significantly [2,3].

Gao [4] studied the tensile process of CCG copper by in situ observation and the microstructure of the drawn wire by optical microscopy and transmission electron microscopy (TEM), indicating that the absence of transverse grain boundary, the small-angle grain boundary character as well as the dislocation cells and deformation twinning developed along specific direction lead to the excellent cold-work extensibility of CCG copper. Deformation

texture has a key influence on the flow behaviors of strained materials besides microstructure, especially in the intense plastic deformation process like cold drawing and cold rolling during which texture components develop significantly and evolve differently within different original microstructures. For example, the volume fractions of $\langle 111 \rangle$ and $\langle 100 \rangle$ fiber texture components were 30% and 60%, respectively, within equiaxed polycrystalline copper at a drawing strain of 1.3 [5], while single-crystal copper fabricated by CUS maintains a majority of $\langle 100 \rangle$ fiber at a drawing strain of 1.96 [6]. The CCG copper possesses a solidification texture with $\langle 100 \rangle$ fiber along the solidification direction, which is similar to the single-crystal copper. Based on the qualitative characterization of the microstructure evolution [4], the features of texture development and stored energy of different texture components are investigated here to discuss their influence on the deformation behaviors and the flow stress, so as to establish the quantitative relationship between processing, microstructure and deformation behaviors, and illuminate the essential results of the excellent cold-work extensibility of CCG copper from the view of texture evolution.

2. Experimental procedure

CCG copper rod with a diameter of 10 mm was fabricated with 99.99 wt% pure copper by CUS technique. The as-cast rod was

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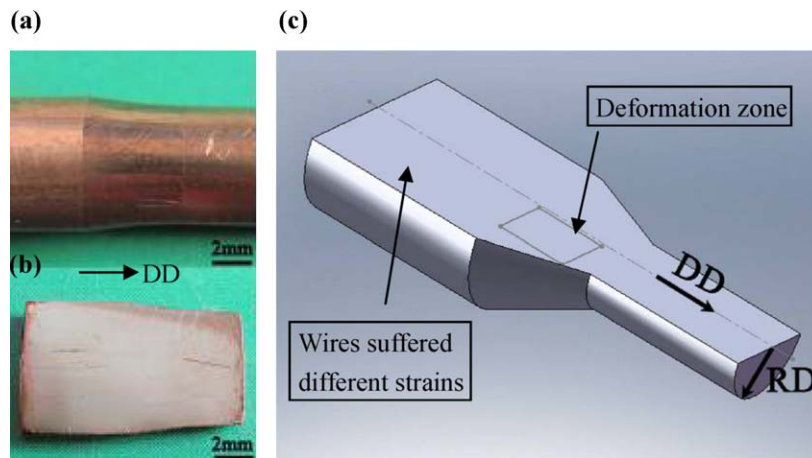


Fig. 1. Photos of (a) a drawn rod and (b) a longitudinal section of the sample after the second pass, and (c) a schematic diagram, a marked deformation zone and the drawing direction (DD) and the radial direction (RD) are marked.

then cold-drawn with a hydraulic-driven drawbench at a speed of 5 mm/s at room temperature. After 12 passes, the rod was drawn into a 2.25 mm-diameter wire. For EBSD analysis of the deformation zone, the drawing was stopped at the middle way in each pass and then the drawn sample was pulled out from the entrance side of the die. As an example, Fig. 1(a) shows a photo of a sample after the second pass. The samples were cut by an electric sparking machine along the longitudinal direction through the center plane. Fig. 1(b) is a photo showing the longitudinal section, while Fig. 1(c) shows schematically the longitudinal section, in which a deformation zone is marked. Due to the axial symmetry of wires, only one half areas of longitudinal sections were examined by optical microscopy and EBSD.

All samples were mechanically polished, electropolished in a chemical solution with 100 ml H_3PO_4 , 100 ml $\text{C}_2\text{H}_5\text{OH}$, 200 ml H_2O , 2 g NH_2CONH_2 , 20 ml $\text{CH}_3\text{CH}(\text{OH})\text{CH}_3$, and then etched by 5 wt% FeCl_3 -ethanol solution. A Nikon ECLIPSE LV150 optical microscope was used in optical observation. The EBSD characterization was conducted with a FEI-SUPRA55 scanning electron microscope equipped with a electron back scattered pattern analysis system. For the texture measurements and misorientation angle statistical analysis, large areas up to 4.7 mm^2 were investigated by EBSD with step-sizes between 5 and $15 \mu\text{m}$. For the microstructure determination, individual areas up to $1600 \mu\text{m}^2$ were studied using step sizes between 0.05 and $0.25 \mu\text{m}$, with at least four areas investigated for each sample. The analysis of EBSD data was performed by the HKL Channel 5 software.

3. Results and discussion

3.1. Micro-texture evolution

Optical micrographs of the as-cast copper rod with CCG microstructure are shown in Fig. 2. The columnar grains have an

average diameter of 1–2 mm and they are elongated along the solidification direction (SD).

Fig. 3 shows orientation-imaging-microscopic (OIM) maps and corresponding inverse pole figures (IPFs) of the as-cast bar and drawn wires after drawing to $\varepsilon_{\text{VM}} = 0.33, 0.87, 1.43, 1.94$ and 2.98 , respectively, where ε_{VM} is von Mises strain. The areas colored by red, blue and yellow represent the $\langle 100 \rangle$, $\langle 111 \rangle$ and $\langle 112 \rangle$ fiber texture regions along the drawing direction, respectively. The black lines mark the high angle boundaries with misorientation angles above 15° in the OIM maps. The $\langle 111 \rangle$ and $\langle 100 \rangle$ fiber texture regions with their fiber axes parallel to drawing direction (DD) usually developed in drawn copper as two kinds of stable final fibers since copper is an FCC metal with high stacking fault energy [5]. In addition, the $\langle 112 \rangle$ fiber texture regions also developed after drawing, as shown in Fig. 3 by the yellow regions, as a metastable fiber texture. In the orientation maps, however, some $\langle 112 \rangle$ fiber region overlaps with the $\langle 111 \rangle$ fiber region and the used software cannot distinguish the two fibers from the overlaps. For simplification, the overlap region of the $\langle 111 \rangle$ and $\langle 112 \rangle$ fiber was labeled as the $\langle 111 \rangle$ fiber (blue) during calculation since the $\langle 111 \rangle$ fiber is stable. White areas in the OIM maps correspond to regions of other texture. All the other components except the $\langle 111 \rangle$ and $\langle 100 \rangle$ fibers were labeled as (others). As expected, the as-cast OCC copper bar contained a strong $\langle 100 \rangle$ texture along the growth direction as shown in Fig. 3(a). After deformed to a strain between 0.33 and 0.87, strips of $\langle 112 \rangle$ fibers developed within the original $\langle 100 \rangle$ fiber regions, as shown in area A in Fig. 3(b) and (c). High-angle grain boundaries separated the two kinds of fiber texture regions. The $\langle 111 \rangle$ fiber texture region developed firstly near the wire center, as shown in Fig. 3(c). When the true strain was between 0.87 and 1.43, some $\langle 112 \rangle$ fiber components (area B in Fig. 3(d)) dispersed within the $\langle 100 \rangle$ fiber texture regions and between the $\langle 111 \rangle$ and $\langle 100 \rangle$ fiber texture regions (area A in Fig. 3(d)). When true strain was higher

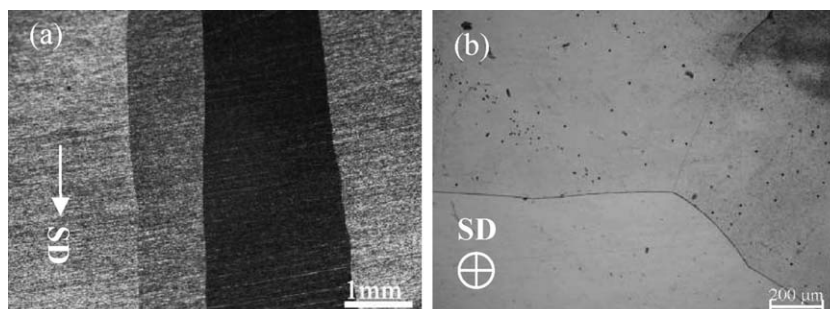


Fig. 2. Microstructure of the as-cast CCG copper rod: (a) longitudinal section, (b) transverse section.

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