Effect of deformation techniques on the microstructure and mechanical properties of a copper alloy

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Effect of deformation techniques on the microstructure and mechanical properties of a copper alloy

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Abstract. The microstructure and mechanical properties of a Cu-0.25%Mg alloy subjected to either equal channel angular pressing (ECAP) or combined cold working, including ECAP followed by rolling and then drawing at room temperature, were investigated. ECAP led to the formation of strain-induced boundaries and the development of ultrafine equiaxed grains with an average size of about 0.6 μm after 4 passes. The microstructure after the combined cold working included fibrous grains elongated in the rolling/drawing direction with a sharp texture containing <001> and <111> fibers. The transversal grain size after combined cold working to a total strain of 5.7 achieved 0.43 μm. The yield strength and ultimate tensile strength after ECAP to a total strain of 9.6 were 570 and 600 MPa; whereas those after combined cold working to a total strain of 8.7 were 745 and 780 MPa, respectively. The reason of the difference in mechanical properties was discussed.

1. Introduction

Cu-Mg alloys are widely used materials for electrical application due to their high electrical conductivity and significant work hardening [1-2]. Adaptation of severe plastic deformation (SPD) techniques as appropriate treatment can improve the combination of strength and electrical conductivity [3-5]. SPD techniques, for example, equal channel angular pressing (ECAP), high pressure torsion, multiple forging, etc. lead to an increase in the dislocation density, the formation of new strain-induced grain and subgrain boundaries [6-7]. The grain refinement and high dislocation density caused by SPD should improve strength without reduction of electrical conductivity in Cu-Mg alloys. Therefore, the combination of the SPD technique with common deformation methods such as rolling or drawing could be of practical significance and deserves special scientific investigation. The aim of the present work is to study the microstructure and mechanical properties of a Cu-Mg alloy after ECAP or combined cold working including ECAP followed by cold rolling and cold drawing.

2. Experiment

A Cu-0.25%Mg alloy was investigated. Original ingots were forged at 800 °C to a total strain of 1.4 and rolled at 450 °C to a total strain of 1. Then, a part of the samples was subjected to ECAP at room temperature to 1, 2, 4 and 8 passes via route B_C with an intersection angle of the matrix channels 90°.

The total strain after 1 ECAP pass was about 1.2. The other part of the samples was cold worked by 1 pass of ECAP followed by cold rolling (CR) to a total strain of 1.5 and then cold drawing (CD) to total strains of 1.5-5.8.

Microstructure investigations were carried out using a Nova NanoSEM 450 scanning electron microscope equipped with an electron backscattered diffraction (EBSD) device. The samples for EBSD analysis were electro-polished in 25% HNO_3 and 75% CH_3OH electrolyte at a temperature of -20 °C and a voltage of 10 V using a Tenupol 5 equipment. The average grain and subgrain size, fraction of high-angle boundaries (HAB), ultrafine grained structure (grain size below 2 micron), average misorientation angle, dislocation density, Kernel average misorientation (for scan step of 200 nm) were calculated using OIM Software. The mechanical properties were studied using an Instron 5882 machine with specimens having the following relationship between the gauge length *l* vs cross-section area *F*: $l=5.65F^{0.5}$. The initial strain rate was 2×10^{-3} c^{-1}.

3. Results and discussion

Microstructure evolution

The original microstructure of the copper alloy after forging at 800 °C and rolling at 450 °C consisted of equiaxed grains with a size of about 3.3 μm and numerous annealing twins. The HAB fraction was about 0.32. 1 pass of ECAP at room temperature led to the formation of new strain induced low-angle boundaries (LAB) and to the elongation of initial grains (Figure 1). Naew ultrafine equiaxed grains appeared, forming chains along initial grain boundaries. Further ECAP resulted in transformation of LAB into HAB and promoted the development of an ultrafine grained microstructure. A homogeneous microstructure with a large HAB fraction and a crystallite size of about 0.5 μm was formed after 4 ECAP passes. The Taylor factor distribution was characterized by two maximums, i.e., relatively small maximum for 2.5 and huge one for 3.3, which did not change significantly with increasing the number of ECAP passes.

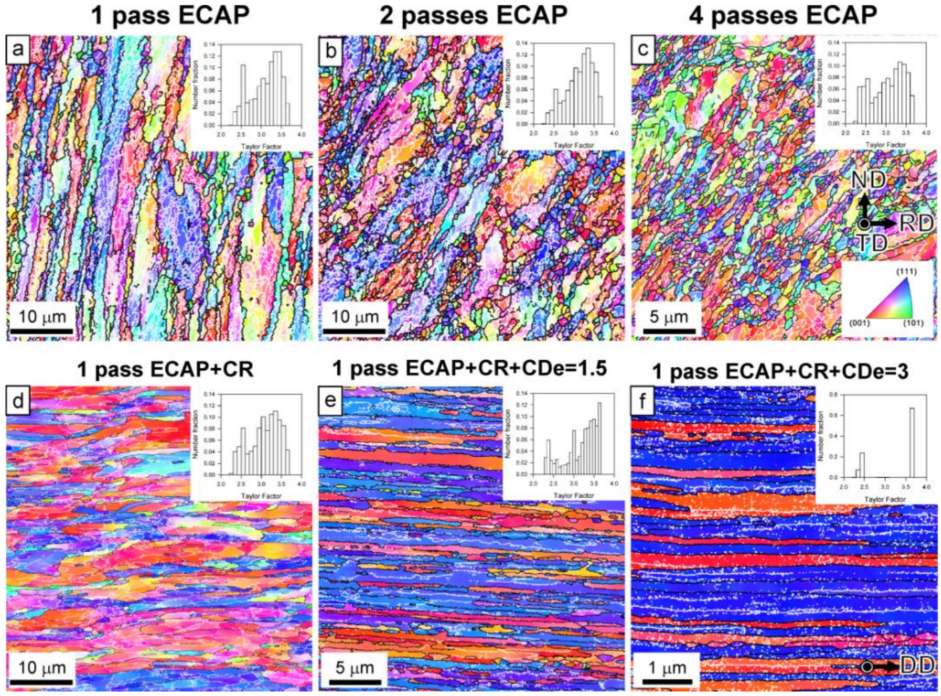

Figure 1. Microstructure evolution during 1 (a), 2 (b) and 4 (c) ECAP passes and combined cold working by 1 pass of ECAP with cold rolling (CR) to total strain of 1.5 (d) and cold drawing (CD) to total strains of 1.5 (e) and 3 (f) of the Cu-Mg alloy. Black and white lines represent HAB and

LAB, respectively. Colors indicate the crystallographic direction along the drawing direction (DD) or transversal direction (TD).

Cold rolling after 1 ECAP pass lengthened the grains along the rolling direction and flattened them in the normal one. Further cold drawing was accompanied by a decrease in the transversal grain size and an increase in the HAB fraction. A sharp crystallographic texture contained <001> and <111> fibers was observed. A fibrous microstructure with a transversal grain size of about 0.3 μm was formed after cold drawing to a strain of 3.0. Distribution of Taylor factor after cold rolling had a huge maximum for 3.2-3.5, which increased with drawing. Bimodal distribution of Taylor factor with maximums at 2.4-2.5 and 3.6 was observed after drawing to a strain of 3.0. Grains with strong fibers of <001> and <111> corresponded to Taylor factors of 2.4-2.5 and 3.6, respectively.

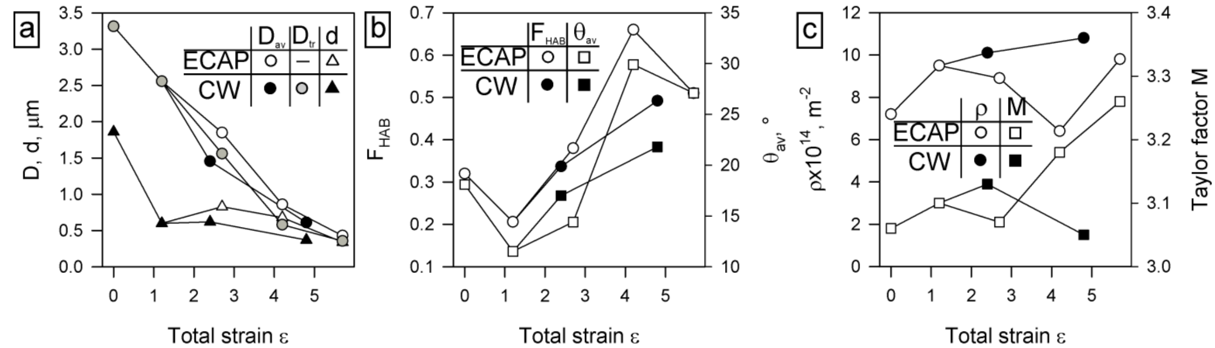

Figure 2. Effect of strain on the average (D_{av}) and transversal (D_{tr}) grain size, subgrain size (d) (a), fraction of HAB (F_{HAB}), average boundary misorientation angle (θ_{av}) (b), dislocation density (ρ) and Taylor factor (M) (c) of the Cu-Mg alloy.

Plastic deformation refined the microstructure (Figure 2). The difference between grain size and subgrain size decreased with strain. The grain and subgrain sizes were almost the same regardless of the deformation methods after total strains of about 4. The average grain size after ECAP (0.6 μm) was larger than after drawing (0.43 μm). Probably this difference was associated with the smaller total strain for ECAP as compared to combined cold working. The HAB fraction decreased after 1 ECAP pass to 0.21 and then increased with ECAP to 0.5-0.66. Drawing promoted a quick increase in the HAB fraction and average boundary misorientation angles. The dislocation density increased with strain during ECAP from $7x10^{14}$ m^{-2} to $11x10^{14}$ m^{-2} and almost unchanged during drawing (7-9)$x10^{14}$ m^{-2}). The average Taylor factor increased after 1-2 ECAP passes to 3.1 and then decreased to 3.05 as in the initial state after 4 ECAP passes. The combined cold working was accompanied by a gradual increase in Taylor factor with straining that attained 3.26 after a total strain of 5.7.

Mechanical properties after deformation

The microstructure refinement improved substantially the strength properties. After cold deformation the yield strength (YS) tended to approach the ultimate tensile strength (UTS) irrespective of the processing technique. ECAP was accompanied by gradual strengthening of about 20-30 MPa per unit strain, while drawing provided strengthening of about 40-60 MPa for the same strain increment. So, the difference in UTS after a total strain of about 8 for ECAP and drawing was almost 180 MPa. The maximum YS/UTS of ECAPed and drawn samples achieved 570/600 MPa and 745/780 MPa, respectively. Elongation dramatically decreased with strain to 1% and 5 % for drawing and ECAP, respectively.

The difference in strength after ECAP and drawing could be attributed to different deformation microstructures. A fibrous microstructure with small transverse grain size and sharp texture provided high strength. The strength (σ) should correlate with the grain size (D) according to the Hall-Petch relationship [8]:

$$\sigma = \sigma_0 + k_y D^{-0.5} \quad (1)$$

where σ_0 and k_y are constants of material. The texture should lead to strengthening due to the change of the Taylor factor (M) in dislocation strengthening by the Taylor equation [9]:

$$\sigma = \sigma_0 + \alpha M G b \rho^{0.5} \quad (2)$$

where G is Gibson modules, b is Burger vector, ρ is dislocation density. The grain reorientation with <111> along the drawing direction corresponded to an increase in the Taylor factor and was accompanied by drastic strengthening. Figure 3 shows that both grain refinement and texture amplification resulted in high strength of the Cu-Mg alloy after drawing.

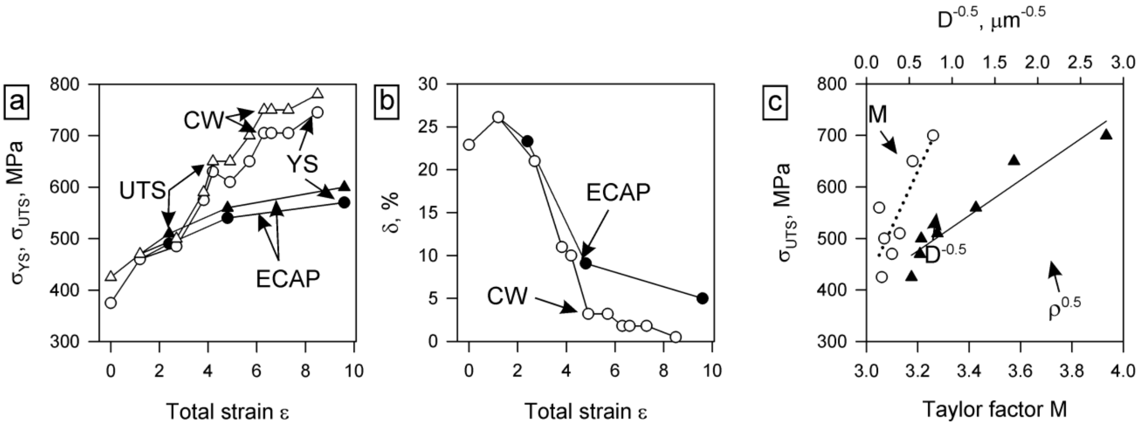

Figure 3. Effect of total strain on the yield strength (σ_{YS}), ultimate tensile strength (σ_{UTS}) (a), and elongation (δ) (b) of the Cu-Mg alloys along with relationships between σ_{UTS} and D or M (c).

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