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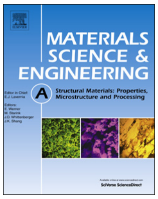

Deformation behavior and microstructure evolution of pure Cu subjected to electromagnetic bulging

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ABSTRACT

In this paper, pure Cu sheet with thickness of 1 mm was electromagnetically budged to form a conical shape workpiece. The deformation behavior and the microstructural evolution of the Cu sheet under electromagnetic bulging were systematically studied using strain analysis, optical microscopy (OM), electron backscattered diffraction (EBSD) and transmission electron microscopy (TEM). It is found that the strain distribution in the workpiece is quite un-uniform from the bottom to the top due to the inhomogeneous electromagnetic pressure generated by the spiral coil. The characterization of microstructure reveals that the bulge deformation of the Cu sheet is governed by dislocation multiple slip and cross slip, which cause finally the formation of cell structures. However, the size and the boundary width of cells are closely related to the plastic strain, i.e., the cell size and boundary width decrease with increasing strain. In addition, low misorientation angle of cells inside the grains increases with increasing strain. This structural evolution is discussed on the basis of the low energy dislocation structures (LEDS) theory.

1. Introduction

Electromagnetic forming (EMF) technique, as a high velocity forming process, has attracted increasing attention in past decades because of its advantages over other conventional mechanical forming techniques, such as the contact-free force application, low springback, high repeatability and enhanced forming limit [1–6]. Due to the high strain rate and non-contact feature with tool, the formed workpiece by EMF may show different deformation behavior and microstructures from those by other high speed forming techniques. However, to the best of our knowledge, only a few works have been devoted to the plastic deformation behavior and microstructure of materials under EMF. Bach et al. [7] investigated the structure changes in pure Al under EMF, and found that the dislocation density increased conspicuously after EMF, and the dislocation cells, regarded as sub-graining structure, were formed when the strain was sufficient high. Liu et al. [8], on the other hand, compared the microstructure evolutions in 5052 aluminum alloy under electromagnetic and quasi-static tension, and observed that the electromagnetic process led to the generation of a high density of dislocations bands and relatively more uniform distribution of dislocations due to the high strain rate effect. In addition, Ferreira et al. [9] tested a 304 stainless steel (which has much lower stacking fault energy than Al and Al alloys) using EMF, and found that the plastic deformation in this case was dominated by twinning due to the easy nucleation of partial dislocations at high strain rate.

Generally, the deformation of high stacking fault energy metals (SFE) (such as pure aluminum with SFE about 200 mJ/m^2 [10]) under EMF is governed by dislocation-slip [7,8], while the deformation of low SFE metals (such as 304 stainless steel with SFE about 17 mJ/m^2) is mainly controlled by twinning [9]. Cu is an FCC metal with a medium SFE (about 78 mJ/m^2) [11] and its deformation mechanism is significantly sensitive to the strain rate. Previous works [12–16] have shown that the deformation of Cu is dominated by dislocations slip under quasi-static loading, but by twinning at high strain rate. EMF is a new high-velocity forming technique and exhibits high strain rate in the range of 10^3–10^4/s [1,6]. However, the deformation mechanism and microstructure evolution of Cu under EMF have not been well understood. In this work, pure Cu sheet with thickness of 1 mm was deformed under electromagnetic bulging. The deformation behavior and microstructural evolution of the bulged Cu are systematically investigated by using strain analysis, optical microscopy (OM), electron backscattered diffraction (EBSD) and transmission electron microscopy (TEM), and the structural evolution is discussed on the basis of the low energy dislocation structure (LEDs) theory, which will provide a better understanding of the deformation behavior under EMF.

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2. Experimental procedure

2.1. Material

A commercial pure copper sheet (purity 99.9%) with thickness of 1 mm was used for electromagnetic bulging. Prior to the test, the sheet was cut into Φ180 mm disk, and then annealed at 973 K for 120 min in argon atmosphere in order to diminish the rolling structures (i.e., rolling induced dislocations and fiber-like structures) and to form nearly equiaxed grains. The average grain size after annealing is about 80 μm and annealed twins are frequently observed in the sample (see Fig. 1).

2.2. Electromagnetic forming

Electromagnetic bulging experiments were carried out with a pulsed electromagnetic forming system at maximum discharge voltage of 25 KV, capacitance of 80 μF and inductance of 200 μH. Fig. 2 shows the schematic diagram of the electromagnetic forming apparatus. The key component is the 72-turn spiral coil (50 mm in diameter and 20 mm in height) in connection with a capacitor. Upon discharging the capacitor, a large current runs through the actuator and induces currents in the Cu sheet. The induction-current inside the magnetic field of the actuator, in turn, generates a huge Lorentz body force in the Cu sheet, which causes plastic deformation of the sheet to form a conical shape workpiece (as shown in Fig. 3b). The maximum magnetic pressure is about 90 MPa in the case of the electromagnetic parameters used in the study. The bulging experiments in each condition were repeated for three times to ensure the credibility of the experimental data.

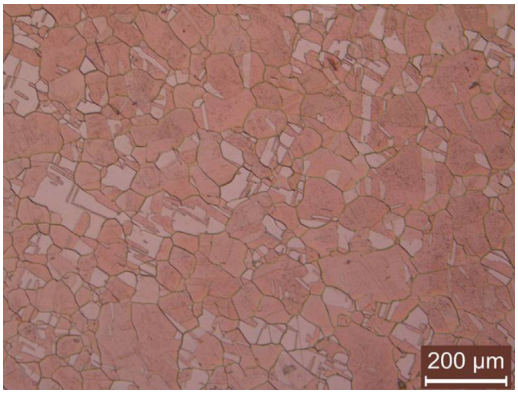

Fig. 1. OM microstructure of the annealed copper sample.

2.3. Strain measurements

Strain analysis was carried out using a commercial software (ASAME Lite Version 4.1). Before testing, circle grids of 2.5 mm diameter were gridded by screen printing on the Cu disks. After the Cu sheet was deformed via electromagnetic force, the workpiece was photographed and the dimension change of the grid was then digitally measured in computer. The 3D coordinates of the grid were determined based on the grid location in the photographs and the camera position when the photographs were taken. As shown in Fig. 3b, the circle grids were changed into collapse due to the non-uniform deformation in the bulging process. Strains were calculated by ASAME Lite based on the difference between the dimensions of the initial grid and the deformed grid. Here, three strains are concerned, the first one is the strain along longitudinal direction, named as major strain (ε_1), the second is the strain along latitudinal direction, named as minor strain (ε_2), and the third corresponds to the thickness change, named as thickness strain (ε_3). According to the geometry illustrated in Fig. 3a, the major strain, minor strain and thickness strain are defined as [17]

$$\text{Major strain}: \ \varepsilon_1 = \ln \frac{d_1}{d0},$$

$$\text{Minor strain}: \ \varepsilon_2 = \ln \frac{d_2}{d_0},$$

$$\text{Thickness strain}: \ \varepsilon_3 = \ln \frac{t}{t_0},$$

Based on the above three strains, we can obtain the effective strain [17]:

$$\bar{\varepsilon} = \sqrt{\frac{2}{9}\left[(\varepsilon_1-\varepsilon_2)^2+(\varepsilon_2-\varepsilon_3)^2+(\varepsilon_3-\varepsilon_1)^2\right]},$$

where d_0, d_1, and d_2 are the diameter of the original circles, the length of major and minor axes of the ellipses, respectively (see Fig. 3a), while t_0 and t are the thicknesses of the Cu sheet before and after deformation, respectively.

2.4. Structural characterizations

The microstructure of the electromagnetically bulged Cu sheet was characterized using optical microscope (OM, Leica DM4000), field emission scanning electron microscope (FSEM, FEI Sirion200) equipped with an EBSD system and transmission electron microscope

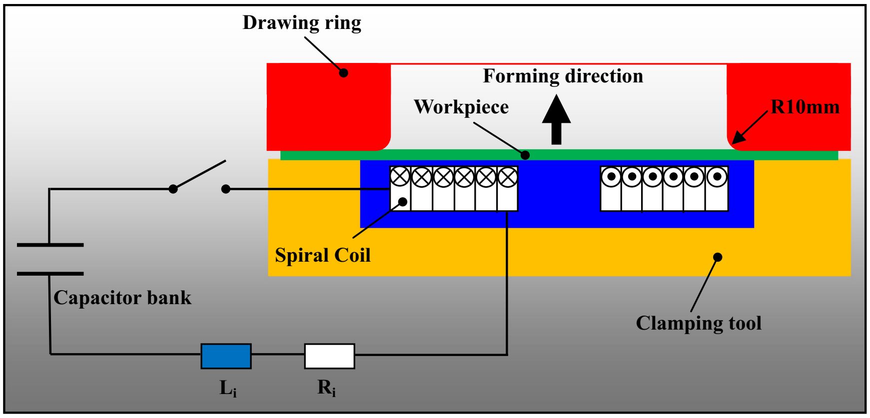

Fig. 2. Schematic diagram of the electromagnetic forming apparatus.