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A high strength and high electrical conductivity bulk Cu-Ag alloy strengthened with nanotwins

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ABSTRACT

A bulk solid solution Cu-5Ag alloy consisting of nanotwins and nanograins was prepared by means of dynamic plastic deformation at liquid nitrogen temperature. Continuous precipitation of Ag occurs in the nanotwins which exhibit higher thermal stability than the nano-grains upon annealing. A tensile strength of 870 MPa and an electrical conductivity of 78% International Annealed Copper Standard are achieved in the annealed nanostructure Cu-5Ag alloy which is strengthened with nanotwins and nanoscale precipitates.

Cu-Ag alloys exhibit outstanding combinations of high strength and high electrical conductivity [1–5]. Most studies are focused on the alloys with more than 15 wt.% Ag, of which abundant Ag phases are embedded in Cu matrix [2–5]. During cold drawing or rolling, the dispersed Ag phases become fine filaments with spacing in the nanoscale. As the strengthening is derived from the fairly large, widely spaced phase boundaries, the tensile strength is highly ameliorated when the imposed strain is extremely high, whereas the diameter of the deformed sample is reduced to ~200 μm [4]. Application of the Cu-Ag dual phase alloys is limited by the high Ag contents and the large plastic strains.

Over the past few years, a novel strategy was discovered to strengthen metals by introducing multiple twins with twin boundaries (TBs) spaced in the nanometer regime [6,7]. These TBs can effectively block the dislocation motion like conventional high angle boundaries (GBs) while having negligible effect on the electrical conductivity. Therefore, the nanotwinned copper exhibited an excellent combination of strength and electrical conductivity. For example, a strength of 610 MPa was achieved in Cu with 95% International Annealed Copper Standard (IACS) when high density of deformation nanotwins was obtained by dynamic plastic deformation (DPD) at liquid nitrogen temperature (LNT) [8].

Most conductive materials are age hardened copper alloys with precipitation strengthening. Although both types of strengthening, i.e. precipitate hardening [9,10] and nanotwin strengthening [6–8], have been investigated separately, a combination of both strengthening mechanisms is seldom. Sun. et al. achieved a high performance Cu-1Cr-0.1Zr alloy with both nanotwins and Cr particles [11]. The approach adopted is that nanotwins were introduced in the Cu matrix embedded with Cr precipitates by plastic deformation. The drawback of this kind of approach is that the strengthening effect of Cr precipitates is weak [11] and the dispersed second phases would suppress the twinning tendency of Cu matrix [12]. The other approach is that the nanotwins can be introduced in the solid solution state, and aging treatment is implemented subsequently to achieve precipitate strengthening. To the authors' knowledge, the effects of aging treatment on the mechanical and electrical properties of nanotwinned age hardenable copper alloys are still unclear.

In this work, a mixed nanostructure containing a high density of nanotwins and numerous nanograins was prepared in a solid solution Cu-Ag alloy by means of dynamic plastic deformation at liquid nitrogen temperature (LNT-DPD). Aging behaviors of nanotwins and nanograins were investigated to prepare high strength and high conductivity Cu-Ag alloy.

The Cu-5 wt.% Ag alloys used in this work were solution-treated at 850 °C for 5 h with water quenching (average grain size ~50 μm). Cylindrical samples with a diameter of 15 mm and a height of 10 mm were processed by LNT-DPD with a strain of $\varepsilon = 2.0$. The DPD setup and processing parameters were described elsewhere [13]. Five groups of DPD samples were annealed for 10 min at the temperature ranging from 200 °C to 400 °C with an interval of 50 °C, respectively. Microstructural observations were carried out using high-resolution TEM in a FEI Tecnai G^2 F20 operated at 200 kV. High angle annular dark field (HAADF) images were obtained in a scanning transmission electron microscope (STEM) mode. The images were formed by electrons which undergo Rutherford scattering proportional to Z^2. Energy dispersive

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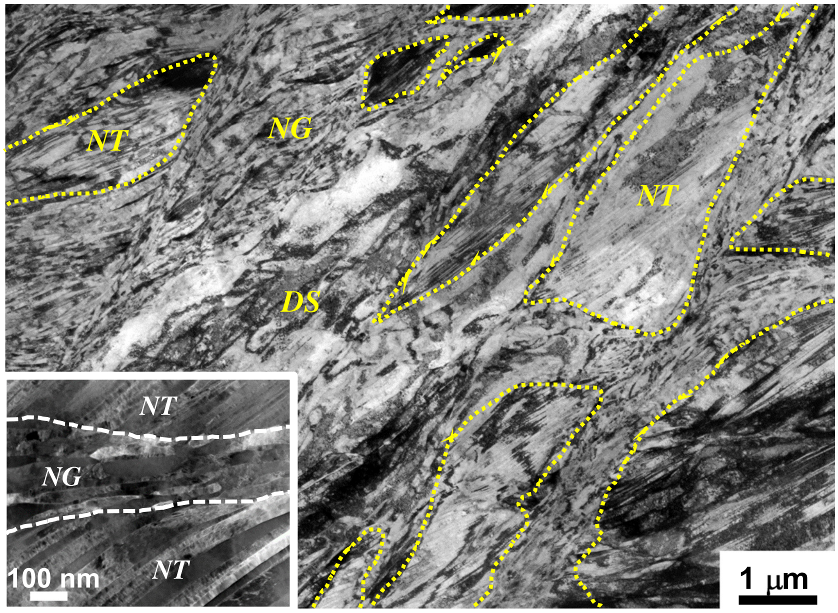

Fig. 1. A typical cross-sectional bright-field TEM image of the LNT-DPD Cu-Ag sample with ε = 2.0. Inset shows the STEM-HAADF image of the DPD sample. The nanotwins, nanograins and dislocation structures are labeled with "NT", "NG" and "DS", respectively.

spectroscopy (EDS) in STEM mode was also performed to confirm the distribution of Ag phase. Vickers microhardness and tensile properties were conducted at room temperature to evaluate mechanical properties. Dog-bone-shaped tensile samples with the gauge dimensions of 5 mm × 1 mm × 0.5 mm were cut perpendicular to the loading direction. The tensile tests were performed on an Instron 5848 micro-tester with a laser extensometer under a strain rate of 5×10^{-3} s^{-1}. The electrical conductivity was measured using a Sigmatest 2.069 digital electrical instrument.

The microstructure of as-DPD samples (Fig. 1) is composed of three types of structures: deformation twins with the twin/matrix (T/M) lamella thickness in the nanometer scale, nano-sized grains and dislocation structures. The nanotwins in bundles are aligned roughly perpendicular to the DPD loading direction. Statistical TEM

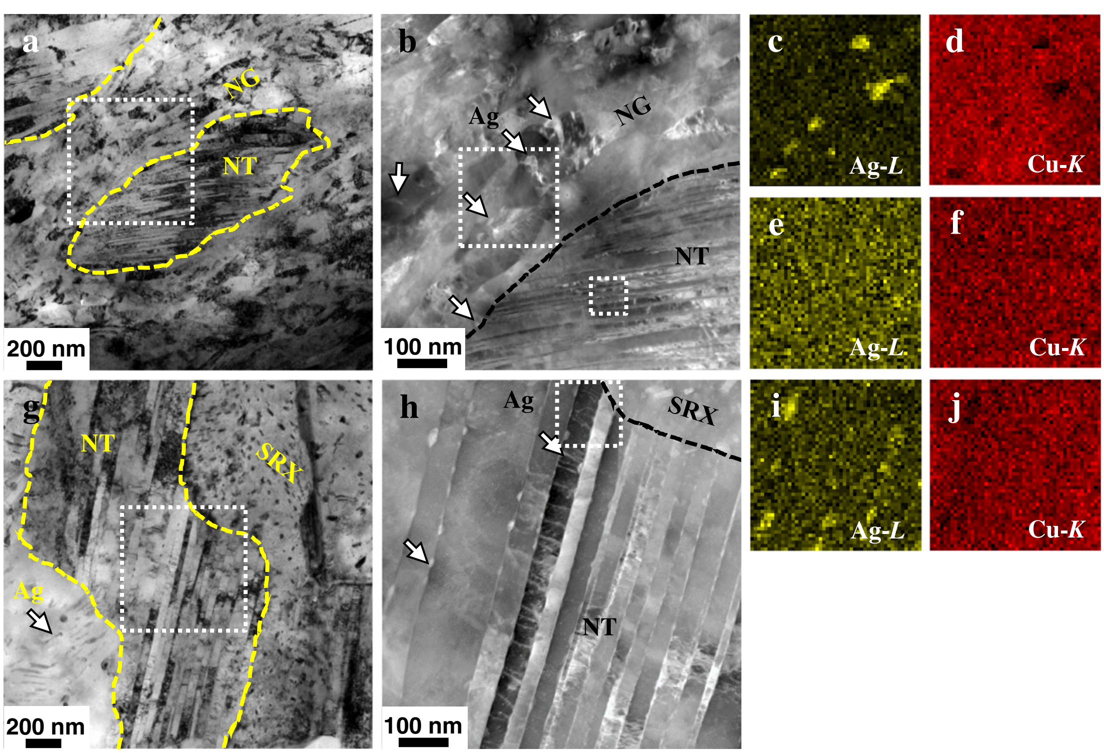

Fig. 2. (a) A bright-field TEM morphology of DPD samples after annealing at 300 °C for 10 min; (b) STEM-HAADF image from the square region in (a). Small arrows indicate the second phase. The element maps taken from the region of nanograins and nanotwins in (b) are shown for (c) sliver, (d) copper, (e) sliver, (f) copper, respectively. (g) A bright-field TEM image and (h) the corresponding STEM-HAADF image of DPD samples after annealing at 400 °C for 10 min. The static recrystallization is labeled with "SRX". Element maps taken from the region of nanotwins in (h) are shown for (i) sliver, (j) copper.