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A high strength and high electrical conductivity bulk CuCrZr alloy with nanotwins

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A bulk nanostructured CuCrZr alloy consisting of nanotwins and nanograins was prepared by dynamic plastic deformation at liquid nitrogen temperature. A tensile strength of 700 MPa and an electrical conductivity of 78.5% International Annealed Copper Standard are obtained in the nanostructured CuCrZr alloys processed by means of this one-step deformation without aging treatment. The reason for the increased strength without the sacrifice of its high electrical conductivity was discussed.

Keywords: CuCrZr; Electrical conductivity; Strength; Nanostructure; Nanotwins

High strength and high electrical conductivity are usually required simultaneously in conductive metallic materials, such as Cu and its alloys. However, these characteristics are mutually exclusive in materials strengthened by conventional methods, such as alloying, strain hardening and grain refinement. Solute atoms of the alloying elements always reduce the electrical conductivity of alloys sharply [1]. Limited strength and poor thermal stability are problems of strain-hardened pure Cu. Hence, precipitation strengthened dilute Cu alloys are developed to achieve an optimized combination of strength, electrical conductivity, thermal stability and wear resistance through aging treatment [2,3]. In recent years, aging has also been implemented after severe plastic deformations to promote grain refinement and precipitation hardening for better mechanical and electrical performance in Cu alloys [4–7]. For instance, a tensile strength of 700 MPa and an electrical conductivity of 77% IACS (International Annealed Copper Standard) were achieved in a CuCrZr alloy prepared by equal-channel angular pressing (ECAP) and aging [4]. However, aging parameters have to be carefully designed and controlled to balance strengthening and sufficient recovery of electrical conductivity because the peak-aging-induced severe lattice distortion brings a strong scattering of electrons, which means an increase in electrical resistance.

An investigation of cryogenically drawn pure Cu wires indicated that a high strength of 580 MPa could be achieved with an electrical conductivity of 96% IACS when the microstructures were refined to the nanoscale with cell structures and deformation twins [8]. A strength of 610 MPa was also achieved in bulk Cu with the same electrical conductivity when a high density of nanotwins was obtained under high strain rate deformation by dynamic plastic deformation (DPD) at liquid nitrogen temperature (LNT) [9]. The high strength of LNT-DPD Cu is attributed to the nanoscaled microstructure and particularly the high density of nanotwins. Twin boundaries, which have similar strengthening effects as high angle grain boundaries but lower intrinsic electrical resistivity [10], are considered to be an effective microstructure in strengthening pure Cu with a limited sacrifice of electrical conductivity.

In this work, attempts were made to introduce nanostructures into the CuCrZr alloy with a one-step deformation process under high strain rates at LNT without aging, i.e. by LNT-DPD. A strength of 700 MPa and an electrical conductivity of 78.5% IACS were achieved with a microstructure consisting of nanotwins and nanogrians. The effects of both deformation conditions and Cr particles on the microstructures and properties are discussed.

A commercial C18150 alloy was chosen in this work with 1.0 wt.% Cr and 0.1 wt.% Zr. The solubility of Cr in Cu varies from 0.27 wt.% at 1273 K to less than 0.02 wt.% at room temperature [11]. This is frequently used to strengthen alloys through age hardening. In this work, however, the alloy was annealed at 873 K for 2 h before deformation instead of the conventional processes of solid solution and quenching, to achieve sufficient precipitation of Cr from the matrix and therefore a better electrical conductivity. The annealed alloy, which has an electrical conductivity of 84.2% IACS, is structurally characterized by

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well dispersed spherical Cr particles embedded in pure Cu matrix (0.05 wt.% Cr at 873 K [11]).

Cylindrical CuCrZr samples with a diameter of 10 mm and a height of 17 mm were deformed by LNT-DPD. Each sample was totally immersed into liquid nitrogen until temperature equivalence and then deformed with a strain rate of 10^2–10^3 s^{-1}. The detailed processes can be found in Refs. [12,13]. Samples with the same initial state were also deformed by quasi-static compression (QSC) on a SHIMADZU UH-F1000kNC universal test machine with a much lower strain rate of 10^{-3} s^{-1} at room temperature (RT) for comparison. Disk-like samples were obtained after the DPD or QSC processing. The plastic strain of the treated samples was calculated from the expression $\varepsilon = \ln(h_0/h)$, where h_0 and h are the initial and final heights of samples, respectively. Disks with a diameter of around 30 mm and a thickness of 2.3 mm were obtained when the strain was 2.0. A JEOL JEM-2010 transmission electron microscope (TEM) operated at 200 kV was used to characterize the microstructures. Vickers microhardness and tensile properties were conducted at RT to evaluate their mechanical properties. The dog-bone-shaped specimens used in the tensile tests were cut parallel to the plane surface of the disks. The total length of the dog-bone-shaped tensile samples was 17 mm and the gauge dimension was 5 mm × 1 mm × 0.5 mm. Tensile tests were conducted on an INSTRON 5848 microtester with an MTS LX300 laser extensometer under an initial strain rate of 5×10^{-3} s^{-1}. The electrical conductivity was measured through the standard four-probe method at RT on CuCrZr sticks which were cut parallel to the plane surfaces of disks, and had a cross-section of 2 mm × 1 mm and a length of about 30 mm. At least three specimens of each state were tested for mechanical and electrical property evaluations. Furthermore, the electrical conductivity of each specimen was measured at least three times.

The Cu matrix of the CuCrZr samples underwent major plastic deformation during both the LNT-DPD and RT-QSC processes. High density dislocations in tangles and cells were induced in the matrix of LNT-DPD CuCrZr samples at a strain of 0.3. Deformation nanotwins in bundles were also observed. With increasing strain, lamellar structures formed, and the lamellar thickness decreased gradually. Some lamellae with nanoscale thickness further developed into roughly equiaxed nanograins via formation of dislocation boundaries along the thickness direction. When the strain exceeded 0.9, a mixed microstructure was obtained in the matrix consisting of nanotwins in bundles, lamellar structures and nanograins. Meanwhile, finer nanotwins formed widely inside the thick lamellae. The mixed microstructure with the strain of 2.0 is shown in Figure 1a. The nanotwins in bundles are aligned roughly perpendicular to the loading direction. The volume fraction of nanotwins in bundles is approximately 20%. The measurements on microstructure sizes were conducted using more than 460 twins or grains in a series of TEM images. Measurement of the grain sizes of nanograins was conducted on the dark-field images. The average thickness of twins in bundles was about 25 ± 14 nm. The average size of the nanograins was about 47 ± 19 nm and the average thickness of lamellar structures was about 118 ± 51 nm. The fine nanotwins in the thick lamellae aligned at an angle of about 50° to the lamellae (Fig. 1b). A high density of dislocations was observed in the nanograins and nanotwins.

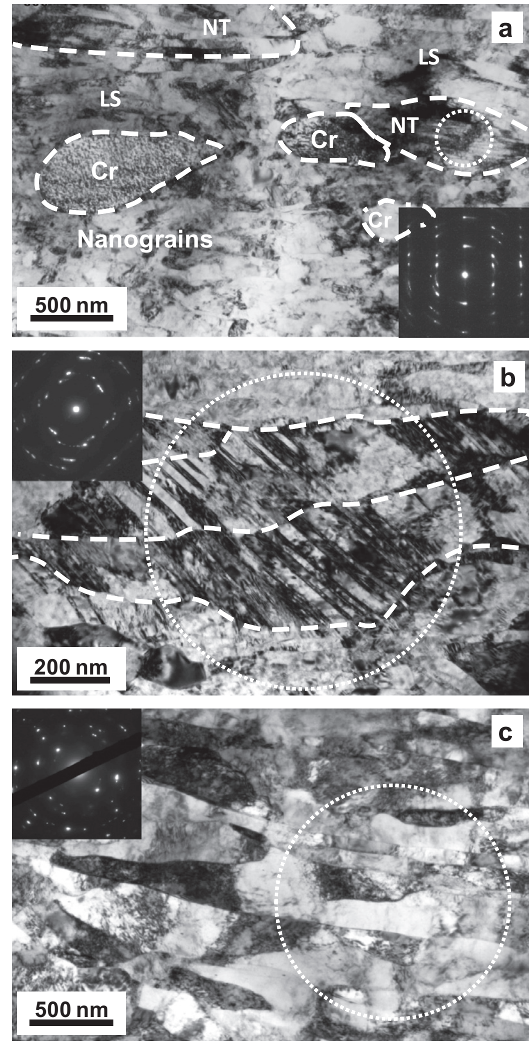

Figure 1. TEM morphology of (a) the mixed nanostructure, (b) twinning inside the lamellae of the LNT-DPD CuCrZr sample with a strain of 2.0 and (c) lamellar structure in the RT-QSC CuCrZr samples with the same strain. Inset are SAED patterns of the areas marked with a circle. Twins were observed along [110]. NT: nanotwins in bundles; LS: lamellar structures.

The Cr particles were also deformed in shape, but fragmented particles were seldom observed.

The microstructure of the RT-QSC CuCrZr samples with a strain of 2.0 is characterized by lamellar structures (Fig. 1c), which is consistent with the typical feature of metals deformed with a small strain at low strain rates [14,15]. The average thickness of the lamellae is about 197 ± 94 nm, which is larger than that obtained in the LNT-DPD CuCrZr sample (118 ± 51 nm). A high density of dislocations can also be observed in tangles in the lamellae, but no twin was found in the RT-QSC samples. Unlike the RT-QSC CuCrZr, the formation of the mixed nanostructures in the LNT-DPD samples is attributed to the deformation condition of LNT-DPD treatment. High strain rates and cryogenic deformation could induce more dislocations and restrain their dynamic recovery, bringing the lamellar thickness in the LNT-DPD sample down to the nanoscale. Furthermore, the high strain rate and cryogenic deformation facilitate twinning in the CuCrZr samples with the layer thickness in the nanoscale.