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Non-deformation recrystallization of metal with electric current stressing

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ABSTRACT

Recrystallization can be achieved by annealing or electric pulse treatment of plastically deformed metals. The deformation produces a high dislocation density to facilitate nucleation. The present study, however, reports that direct electric current stressing can produce high dislocation density in metals, as revealed by EBSD and high resolution TEM analysis. Recrystallization of brass was thus triggered *in situ* by the generated Joule heat. The microstructure variations, grain refining, and microhardness of the brass were investigated after non-deformation recrystallization. A 75% improvement in grain size refinement and a 28% enhancement in microhardness in comparison with the annealed as-prepared specimen was achieved with a 4 h, 10 cycle current stressing-quench treatment at a current density of 14000 A/cm^2.

1. Introduction

Recrystallization is one of the most important processes for diminishing defects in deformed metals and alloys and thus modifying their microstructure and properties. Recrystallization may take place by virtue of nucleation at high strain sites, for instance, dislocation sites and grain boundaries. Hard work deformation has been conducted to produce high volumes of dislocations in the matrix in order to trigger recrystallization. High dislocation density will cause stress and thus strain energy within the matrix. The stress, σ_i , caused by the dislocation interactions during hard deformation can be expressed as [1],

$$\sigma_i = M\alpha\mu b\sqrt{d_i} \tag{1}$$

where d_i is the average dislocation density; b is the Burgers vector; α is the dislocation interaction constant; μ is the shear modulus, and M is the Taylor factor. Appropriate annealing will induce nucleation and thus recrystallization at high strain dislocation sites. The driving force for recrystallization, P, is the sum of long-range elastic strains and the dislocation cores [2,3]. The driving force is correlated with the dislocation as [3],

$$\mathrm{P} = \mathrm{d}\mu b^2 \tag{2}$$

where μ is the shear modulus. Both Equations (1) And (2) indicate the importance of dislocation in recrystallization.

A high dislocation density is required to facilitate the recrystallization of metal. Severe plastic deformation [4] induces a high volume of dislocations that act as the nucleation sites for recrystallization. Hard work followed by annealing used to cause recrystallization is an applicable practice for grain refining [5–7]. The hard work methods used to produce severe plastic deformation include equal channel angular pressing [8], high pressure distortion [9], and accumulative roll bonding [10], among other methods. Recrystallization can also be achieved by electric pulse treatment on mechanically deformed metals [11–13], such as a 60% roll reduction. The large Joule heat thus produced by an electric pulse at highly deformed sites supplies the energy needed for recrystallization [14,15]. The recrystallization temperature of a deformed metal depends on the extent of the dislocations produced [16,17]. Dynamic recrystallization occurs when the dislocation reaches the critical dislocation density [1]. A dislocation density of 4.6 × 10^{14} m^{-2} can be produced in a cold-worked V4Cr4Ti alloy [18]. An even higher dislocation density of 1.2 × 10^{15} m^{-2} has been produced in an alloy with a 90% roll reduction [19]. Hard work, however, is not applicable for fabricated subjects such as casts, machined, or forged products, among others.

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No practical process is currently available for producing high dislocation density in a solid metal without deformation. It would be of interest to be able to induce the movement of atoms to form dislocations without mechanical deformation. The electric current stressing on metal will induce electromigration force F_{em} [20],

$$F_{em} = e\, Z^{*} E\, \rho\, j \tag{3}$$

where Z^* is the effective charge; e is the electron charge; E is the electrical field; ρ is resistivity, and j is the current density.

The electromigration force acts on the atoms directly, which causes movement of the atoms. The electromigration will result in a vacancy on the cathode side and a hillock on the anode side of a metal circuit [21]. It is the impact force that causes atom movement *in situ* without the need for an external mechanical force, and thus no deformation occurs. Previous studies have shown that electric current stressing can cause large strain within solders and even in intermetallic compounds [22–24]. The strain produced can be greater than 0.2%. The high strain estimated from the d-spacing variation, as indicated by X-ray diffraction, reflects the displacement of atoms upon current stressing. The electric current stressing produces a high dislocation density within the metal that even causes a diminishing of X-ray diffraction peaks upon current stressing [22]. In the present study, a method for producing high dislocation density in brass with electric current stressing without the need for plastic deformation was adopted. The non-deformation recrystallization took place simultaneously, as it was triggered by the generated Joule heat. This is an innovative approach to induce recrystallization. The grain boundary misorientation, grain size reduction, twin structure formation, and the hardness variation were investigated for the recrystallized brass in comparison with an annealed as-prepared specimen.

2. Experimental method

A 20 mm × 2 mm x 0.025 mm commercial Cu36Zn brass strip was aged at 450 °C for 12 h to release the stress and stabilize the microstructure. The as-prepared Cu36Zn alloy exhibited a single phase Cu solid solution. The use of single phase brass avoids possible interference from dissolution and recrystallization of the second phase [25,26]. The brass strip was connected to Cu wires by soldering at both ends for electric current stressing, as shown in Fig. 1. The specimen was fixed on a glass carrier with silicone tape. The current density was chosen based on the results of a strain variation study with an *in situ* synchrotron XRD (BL17B1 Beam Line of the National Synchrotron Radiation Research Center, Hsinchu, Taiwan) investigation to be described later. The strips were quenched in liquid nitrogen prior to stopping the electric current to dissipate the excessive Joule heat and to freeze the microstructure. The current stressing and liquid nitrogen quench were conducted periodically for various cycles. The average grain size and the grain orientations of the brass strip were investigated with an EBSD (Electron Back Scattered Diffraction) analysis. The lattice structure and the dislocations in the specimens were investigated with a high resolution transmission electron microscope (HRTEM) assisted with an inverse Fourier Transform to better reveal the lattice images. The microhardness was measured at a load of 25 g for 15 s. The nano-indentation investigation was conducted with an indentation depth of 400 nm.

3. Results and discussion

3.1. Recrystallization microstructures

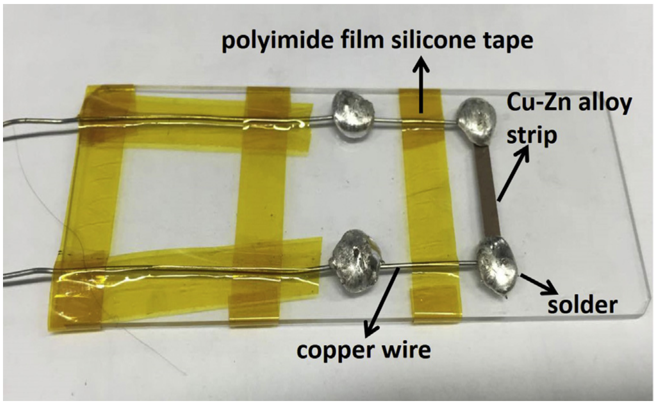

Fig. 1. The experimental setup for the electric current stressing. The strip was connected to a copper circuit wire with solder at both ends. The circuits were fixed on a glass carrier with tape.

Electromigration force may cause movement of atoms off the lattice positions. The Joule heat causes thermal expansion of the material. The combination of electromigration and thermal expansion may induce dislocation. The formation of dislocation gives rise to strain in the metal. The strain can be estimated from the variations in the lattice spacing, as measured by X-ray diffraction [27]. It was reported in previous studies [22,23] that the strain in solders will increase upon electric current stressing. There exists a critical current density above which the strain will increase rapidly. The high strain induced in a solder above the critical current density has been shown to be accompanied by high dislocation density [23]. The strain variations in the brass under consideration in this study, as presented in Fig. 2, were measured for various lattice planes in current density ranges of 4000–14000 A/cm^2. It can be seen that the critical current density exists in the range of 6400–7360 A/cm^2 for lattice planes (111), (200), and (220). The temperature of the specimen achievable after current stressing at 14000 A/cm^2 was found to be 105.7 °C. The average strain obtained for the specimen aged at 105.7 °C was around 0.22%, compared with that of around 0.30% obtained at 14000 A/cm^2, as shown in Fig. 2. This is indicative that current stressing does contribute to the strain increase in the specimen. The recrystallization investigations discussed in the following passages were conducted at 14000 A/cm^2.

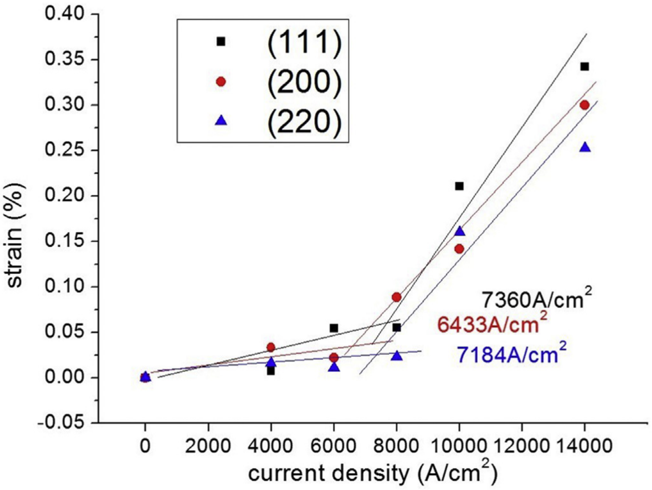

Fig. 2. The strain variations on various planes, measured with XRD, of the brass with respect to electric current density.