Journal of Alloys and Compounds 586 (2014) S377–S380

Contents lists available at SciVerse ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jalcom

Deformation-induced alloying of Cu sheet with Al using ball collisions

I.V. Shchetinin [a], J.M. Yoon [b], S. Romankov [b,*]

[a] National University of Science and Technology "MISiS", 119049 Moscow, Russia
[b] Devision of Advanced Materials Engineering, Chonbuk National University, Jeonju 561756, South Korea

ARTICLE INFO

Article history:
Available online 27 March 2013

Keywords:
Ball impacts
Severe plastic deformation
Grain refinement
Diffusion
Nanostructured materials

ABSTRACT

Cu sheet was alloyed with Al using ball collisions at room temperature and ambient atmosphere. Al was introduced into the Cu sheet as contamination from the grinding media. The idea here was first to coat the balls with Al by mechanical alloying and treated the surface of the Cu sheet using ball collisions. The Al debris from the grinding media was first to adhere to the Cu sheet under the ball collisions and then the deformation-induced diffusion and intermixing of the elements resulted in the formation of the Cu(Al) solid solution. The size of nanocrystalline grains after treatment ranged between 10 nm and 50 nm and an average of about 20 nm. The hardness of the Cu sheet after the treatment was increased more than four times.

1. Introduction

Surface severe plastic deformation (SPD) induced by repeated ball collisions has recently received much consideration as a technique for producing nanocrystalline materials [1–4]. Ball collisions may be effectively used not only for surface nanocrystallization and hardening, but also for the fabrication of coatings [5–10] and surface composites [10,11], cladding and joining [12–14]. One of the problems associated with ball treatment is the impurities introduced into the material as a result of contamination from the grinding media used in the milling process. However, it is thought that contamination can be favorable and effectively used for solid-state alloying and surface modification. In the present work, we have attempted to alloy the Cu sheet with Al using ball collisions. In this work, alloying and cladding were carried out simultaneously to estimate the thickness of the alloyed layer and demonstrate that the combination of the process variants of ball treatment could provide a simple and effective solid-state processing for creation of the new "hybrid" materials [15–17].

2. Experimental details

The experiments were carried out in a hardened-steel vial (volume: 0.4 L) using a mechano-reactor with a frequency and an amplitude of 75 Hz and 3.5 mm, respectively [12,13]. Commercial Ti plate was used as substrates. The dimensions of the plate was $3 \times 100 \times 100$ mm^3. The cladding material was a Cu (99.99%) sheet with a thickness of 0.5 mm. Al was introduced into the Cu surface as contaminants from the grinding media. As is well known, in the early stages of mechanical alloying, the metal powder coats the surface of the grinding medium [18]. The idea here was first to coat the balls with Al and then introduce Al into the surface from the ball. For this purpose, the Al (99.8%) powder was preliminarily milled in a vial for 15 min. Then, the remains of the powder were removed from the vial; thereafter, the Ti plate and a Cu sheet were fixed at the top of a vial and the stack was treated by the balls coated with Al. Fig. 1 shows a schematic illustration of the method.

The structure of the as-fabricated sample was studied by X-ray diffraction (XRD) analysis using a Rigaku diffractometer with Cu Kα radiation. The microstructure and composition of the samples were studied with a scanning electron microscope Jeol JSM-7000F equipped with energy dispersive spectroscopy (EDS). For transmission electron microscopy (TEM) observations, specimens were cut, ground, dimpled, and ion-thinned at low temperatures. The TEM specimens were examined using a JEM-3010 transmission electron microscope operated at 300 kV. Nanoscale local compositional analyses were performed using a FEI TITAN 80-300 transmission electron microscope. The cross-sectional microhardness was measured using an automated load Mitutoyo hardness testing machine at a load of 10 g and a dwell time of 10 s.

3. Results

The ball collisions caused the cold welding of the Cu sheet and the Ti plate. The thickness of the Cu cladded sheet is around 100 μm. The thickness of the cladded sheet is much smaller than the thickness of the initial Cu sheet. The reduced thickness could be attributed to frictional wear and plastic deformation caused by the ball collisions. Cu can be sufficiently plasticized and easily moved throughout the deformation process under the ball collisions. As can be seen in Fig. 5, the pressure developed under the ball collisions was capable of pressing the material even into microsized surface spaces. Joining of the materials under the ball collisions has been considered in [12–14].

Fig. 2 shows XRD patterns of the Cu sheets before and after treatment. In the XRD pattern of the initial Cu sheet, the 200 peak is strongly favored, indicating that the structure of the sheet is textured (Fig. 2a). After treatment, the intensity of the Cu diffraction lines is completely changed, indicating that the rolling texture

---

* Corresponding author. Tel.: +82 632702281.
E-mail address: romankovs@mail.ru (S. Romankov).

0925-8388/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jallcom.2013.03.158

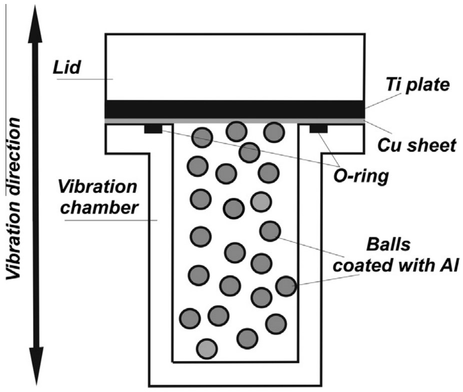

Fig. 1. Schematic illustration of the process.

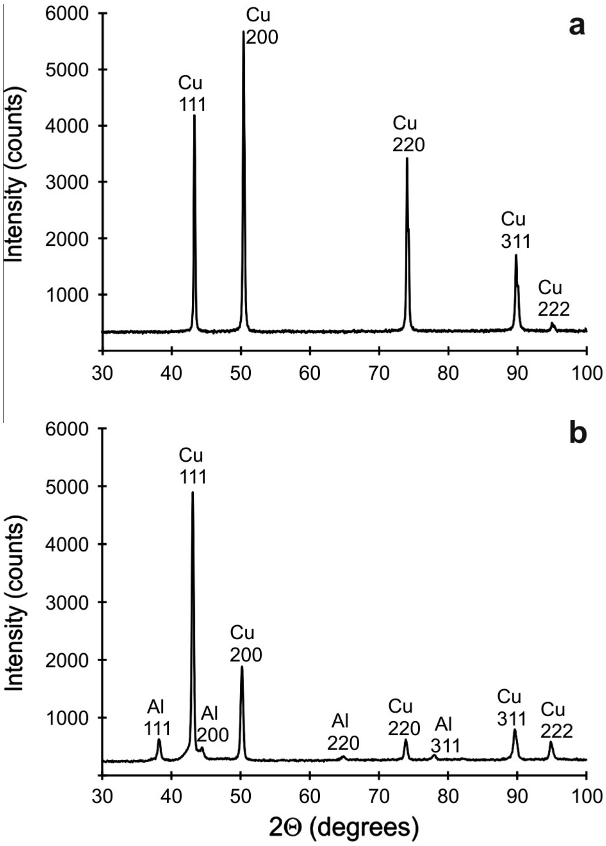

Fig. 2. XRD patterns: (a) the initial Cu sheet and (b) after ball treatment.

was destroyed (Fig. 2b). In addition, XRD analysis detected the lines of the fcc Al crystal structure. Indeed, after the treatment, the surface of the Cu sheet was coated with a thin discontinuous Al layer. Obviously, the XRD analysis detected the thin Al layer. After treatment the value of the lattice parameter of Cu was 0.4% greater than that of the initial Cu plate.

Fig. 3a shows the cross-sectional microstructure of the specimen prepared for TEM observation. The SEM image gives the structure of the Cu sheet at the depth of around 90 μm from the top surface. The EDS analysis showed that the composition of the Cu cladded sheet was around 7.7 wt.% Al, less than 1% Fe and Ti, and the balance Cu. The elemental X-ray map revealed that Al was homogeneously distributed in the sheet on micron-scale level (Fig. 3b). The chemical composition of the cladded Cu sheet matched that of a single phase Al bronze.

The TEM observation revealed that after the treatment the Cu sheet contained equiaxial or elongated nanocrystalline grains with a size range of 10–50 nm and an average of about 20 nm (Fig. 4). The selected-area electron diffraction (SAED) patterns displayed well-developed rings indicating that the material was polycrystalline, with a multiplicity of crystallographic orientations. The analysis of the SAED patterns taken from different areas showed the presence of a fcc Cu crystal structure. Nanoscale EDS analysis indicated that there were variations in chemical composition. The Al and Fe contents ranged from 3 to 6 and from 1 to 2 wt.%, respectively. The Ti concentration was less than 1%. The variation in the contrast in STEM dark field image shown in Fig. 5 may indicate a nanoscale microstructural heterogeneity in the cladded Cu sheet, which can be caused by chemical segregation.

Fig. 6 shows the microhardness of the initial Ti plate, Cu sheet, and the Cu cladded sheet. As can be seen, the hardness after treatment increased dramatically. Increasing hardness of the Cu cladding can result from the combined effects of the reduction of the grain size, solid-solution strengthening and strain hardening.

4. Discussion

The experimental results suggest that Al debris from the grinding media adhered to the Cu sheet under the ball collisions. The hardness of the Cu sheet was much higher than Al, therefore the adhered Al particles could be easily flattened on the surface under the ball collisions. As a result a thin Al layer was formed. The ball collisions induced the plastic deformation of the Cu sheet and caused a strong material flow Fig. 5 [12,14]. Obviously, Cu and Al started intermixing with time and formed a composite layer. Meanwhile, the intense mechanical deformation induced by ball collisions led refinement of the Cu grains to the nanometer scale (Fig. 4). The grain boundaries became a significant volume fraction of the material. Mechanical milling produced a high dislocation density and a large number of vacancies [1–4,18]. The high levels of defect densities, high strain and local temperature increase under the ball collisions evidently promoted the interdiffusion be-

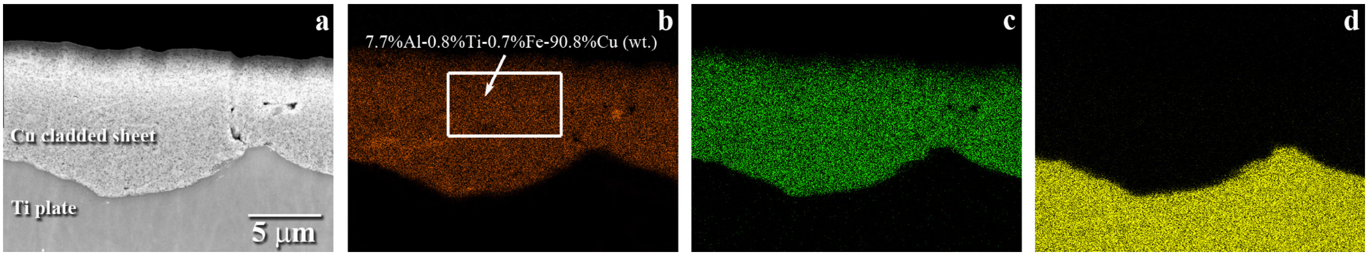

Fig. 3. Cross-sectional microstructure of the specimen prepared for TEM observation: (a) SEM image of the Cu cladded sheet at the depth of around 90 μm from the top surface, (b) elemental Al X-ray map, (c) elemental Cu X-ray map and (d) elemental Ti X-ray map.