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Dry sliding wear behavior of copper with nano-scaled twins

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Abstract

A 99.99 wt.% copper plate with a surface layer containing a high density of nano-scaled twins has been synthesized by means of surface mechanical attrition treatment (SMAT). The friction and wear characteristics of the nano-twinned Cu sample were investigated in comparison with those of equiaxed nanocrystalline Cu and coarse-grained (CG) Cu samples. The tribological properties are markedly enhanced with nano-scaled twin surface layer relative to the coarse-grained form at all the loads and the sliding speeds, which is supposed to originate from the strengthening of twin boundaries. The friction coefficients and wear rates of the nano-twinned and the CG Cu increase slowly with an increasing sliding speed, and slightly decrease at a speed of 0.08 m/s. When the speed exceeds 0.08 m/s, there occurs a steep increase of the friction coefficients and wear rates for all the samples, corresponding to the wearing away of the mixed surface layer.

Keywords: Copper; Nano-scaled twin; Sliding; Unlubricated wear; Surface mechanical attrition treatment (SMAT)

1. Introduction

Pure copper has always attracted considerable interests because of its high electrical and thermal conductivities. But it has some distinct shortcomings such as low hardness and strength, restricting its applications. The strengthening of engineering metals and alloys through grain refinement has long been a strategy for microstructure design [1,2]. In recent years, many experimental observations have led to the discovery that twin boundaries, as a special kind of coherent boundary, may also be effective in blocking dislocation motions, thus strengthening a material similar to conventional grain boundaries [3–5].

In some industrial applications, material's wear resistance can be of primary concern. The tribological behavior of materials has already received much attention in nanocrystalline range in the past decade, and many experimental studies have reported a significant enhancement of the wear resistance in nanocrystalline materials due to grain refinement [6–8]. While to the best of our knowledge, no information is available in the literature concerning the tribological behavior of materials with nano-sized or submicrosized twin structure.

In our experiments, a nano-scaled twin lamella surface layer or a nanocrystalline surface layer on a 99.99 wt.% copper plate was achieved, respectively, by means of different processes of surface mechanical attrition treatment (SMAT) [9,10]. The friction and wear behavior of the nanocrystalline surface layer of Cu have already been investigated in our previous work [8], and the results showed that it exhibited a markedly improved load-bearing ability relative to the coarse-grained form. The major objective of this work is to investigate the sliding tribological behavior of the nano-scaled twin surface layer of copper, and polycrystalline copper with nano-sized grains or coarse grains are involved for a comparison. The wear mechanism and wear rate variations with the applied load and the sliding speed are also discussed.

2. Experimental

The material used in this work is a copper plate (100 mm × 100 mm × 3 mm in size) with a purity of 99.99 wt.%. The annealed sample (at 923 K for 2 h in vacuum) with homogeneous coarse grains was subjected to the SMAT process. The details of the SMAT process were described previously [10,11]. AISI52100 steel balls with a diameter of 8 mm were placed at the bottom of a cylinder-shaped chamber that was vibrated by a generator, with which the balls were resonated to impact onto

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the sample surface to be treated at the upper side of the chamber. The samples were treated under vacuum at room temperature for 5 or 30 min, respectively, with a vibration frequency of 50 Hz. Because of severe plastic deformation at a very high strain rate, the microstructure in the surface layer was effectively refined into the nanometer scale. Different microstructure was obtained in the treated surface as a result of different strain rate. The detailed information of which should be given below.

The microstructure of the surface layer on the SMAT Cu was characterized by using transmission electron microscopy (TEM) on a JEM 2010 electron microscope operated at an accelerating voltage of 200 kV. Thin foil samples for TEM observations were cut from the treated surface layer by using the electro-spark discharge technique and thinned by ion thinning at low temperature. The microhardness of the top surface layer in the SMAT Cu samples was measured by using a Vicker's hardness tester with a load of 5 g and a duration of 10 s.

Sliding wear tests of the SMAT Cu samples were conducted using an Optimol SRV III oscillating friction and wear tester in a ball-on-disc contact configuration. The SMAT Cu discs with a dimension of 8 mm × 8 mm × 3 mm, cut from the treated specimens, slid against WC-Co balls of 10 mm in diameter with a hardness of Hv ∼ 1750. The top surface layer of approximately 3–5 μm in the SMAT samples was removed by polishing carefully to eliminate the surface roughness effect on the tribological behavior. The sliding wear tests were carried out in an ambient environment (room temperature 20–25 °C and a relative humidity 40–50%) without lubricant, at an oscillating stroke of 1 mm, normal loads of 1–11 N, sliding speed of 0.01–0.1 m/s, and a fixed sliding distance of 36 m. The wear tests of the annealed coarse-grained (CG) Cu sample with the comparable roughness were also performed under the same conditions for a comparison.

The friction coefficients were continuously recorded automatically, and those at the steady-state sliding were given in this article. The profiles of the worn surfaces were measured using a surface profilometer (Model 2205, Harbin Measuring & Cutting Tool Group Co. Ltd., China) with a diamond stylus so as to determine the wear volume loss as $V = AL$ and volumetric wear rate as $W = V/NS$, respectively (where A is the worn area determined by its profile, L the oscillating stroke, N the applied load and S is the total sliding distance).

The morphologies of the worn surfaces at different wear conditions were investigated by using scanning electron microscopy (SEM) on a LEQ SUPRA 35 electron microscope at an operating voltage of 20 kV. The samples were cleaned ultrasonically in acetone for about 10 min before SEM observations. Energy dispersive spectroscopy (EDS) was used to analyze the composition of the worn surface.

3. Results and discussion

3.1. Microstructure and microhardness

Fig. 1(a) shows a bright-field TEM image and the selected area electron diffraction (SAED) pattern of the top surface layer in the SMAT 5 min Cu sample [12]. Instead of ultrafine equiaxed grains with random crystallographic orientations in the SMAT 30 min Cu sample [8], the microstructure of the top surface layer in the SMAT 5 min Cu sample is characterized by nano-scaled twin lamellas. In terms of a number of TEM images, a statistic lamella thickness distribution was derived as shown in Fig. 1(b). The average twin lamella thickness of the top layer is about 12 nm. The microstructure at the different depth from the top surface of the SMAT 5 min Cu sample was also determined by means of TEM observations. Fig. 2 shows the variation of twin lamella thickness and grain size along the depth of the two SMAT Cu samples [12]. The thickness of nano-scaled twin layer (with the average lamella sizes below 100 nm) in the SMAT 5 min Cu sample is about 12 μm. In our test, light loads were used, and the

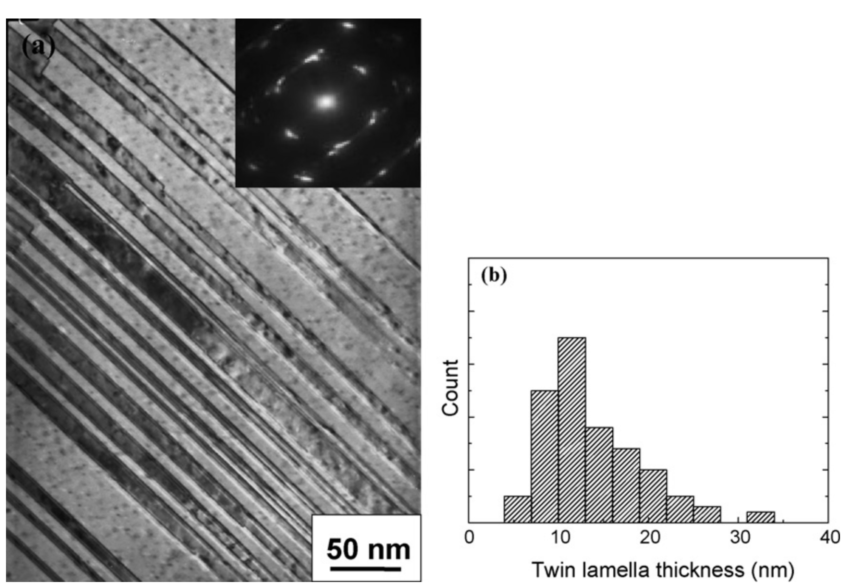

Fig. 1. A bright-field TEM image and a corresponding selected area electron diffraction (SAED) pattern insert (a) and twin lamella thickness distribution (b) of the top surface layer in the SMAT 5 min Cu sample.