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Enhanced mechanical properties in Cu–Zn alloys with a gradient structure by surface mechanical attrition treatment at cryogenic temperature

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ABSTRACT

This paper describes the effects of gradient structure on mechanical properties of Cu–Zn alloys processed by surface mechanical attrition treatment (SMAT) at liquid nitrogen temperature (77 K). This method leads to the formation of a gradient structure with surface fine-grained regions and a coarse-grained interior. In this study, a fine-grained surface layer with a thickness of 10 μm is formed on a coarse-grained Cu–Zn alloy sheet after the cryogenic SMAT process. Microstructural observations and microhardness measurements demonstrate that a significant microstructure refinement in grain size and a gradient increase in hardness from the coarse-grained core to the top surface. Tensile tests at room temperature showed superior strength–ductility synergy for the SMAT sample.

1. Introduction

With the widespread investigations of nanostructured materials during the last decade, a number of experimental methods have shown their great potential in achieving excellent mechanical properties of materials. However, despite nanostructured materials possessing high yield strength, they exhibit significantly lower ductility when compared to their traditional coarse-grained polycrystalline counterparts [1,2]. For the most part, the failures of material mainly occur on surfaces, such as wear, corrosion and fatigue fracture, etc. and as such, these failures are extremely sensitive to the microstructure and mechanical properties of the material surface. Therefore, optimization of the surface microstructure and surface performance is an effective way to reinforce the overall performance and service lifetime of materials [1]. Recent investigations have shown that in a number of systems, surface mechanical attrition treatment (SMAT) synthesize a fine-grained surface layer on bulk metallic materials, without contamination or porosity [3–5]. SMAT is a recently developed process technique based on mechanisms of conventional severe plastic deformation (SPD). It can produce new advanced materials with a gradient structure that gradually change from the interior to surface. The advantage of gradient structures lies in maximizing physical and mechanical properties and minimizing material cost. The gradient structure materials are fundamentally different from their conventional coarse-grained counterparts, possessing high strength and hardness and enhanced physical properties [1,2,6]. Although SMAT processes have been applied to various materials, including Cu [5], Fe [4,7], Ti [8] and stainless steels [9,10], there is very limited data so far to demonstrate the effect of SMAT processing on the Cu–Zn alloys, especially at cryogenic temperature where dynamic recovery and local recrystallization are greatly suppressed [11]. According to the above analysis and the current research [4–6], it can be expected to obtain a superior strength–ductility synergy by generation of a gradient structure on Cu–Zn alloys after the cryogenic SMAT process.

In the present paper, we employ a new cryogenic SMAT process on Cu–Zn alloys and show its advantages in terms of microstructure refinement compared to conventional SPD processing. We show that architecture of gradient structure provides an unique strategy to develop strong-and-ductile materials. The aim of the present study is to discuss the effect of cryogenic SMAT processing

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on the grain refinement mechanism, gradient structure, and resulted mechanical properties of Cu–Zn alloys.

2. Experimental details

Cu–10 wt%Zn, Cu–20 wt%Zn and Cu–30 wt%Zn, with stacking fault energy (SFE) of 35, 18 and 14 mJ/m^2 [12], respectively, were prepared by induction vacuum melting. The cast ingots were hot forged at 700 °C and then were made into plates with the same thickness of 7 mm via hot-rolling. The plates were then annealed at 700 °C for 8 h under argon atmosphere to eliminate mechanical stress and homogenize the microstructure. The homogenized samples were finally rolled to a thickness of 0.6 mm taking reductions of 40 µm per pass. Prior to the SMAT treatment, the Cu–Zn plates were annealed in vacuum at 400 °C for 1 h to obtain homogeneous coarse grains.

Some details of the SMAT set-up and procedure have been described in the other research [3]. This technique is based on the vibration of stainless steel balls. Because of the high frequency of the system, the balls were resonated to impact the sample surface over a short period of time and the strain rate of the top treated surface was close to $10^{2-3}\ s^{-1}$ [5,11]. In this work, the samples were first polished to a mirror finish. Then, SMAT was performed under vacuum at cryogenic temperature for 5 min with a vibrating frequency of 50 kHz with stainless steel balls of 8 mm diameter. The cryogenic SMAT process was conducted on both sides of the Cu–Zn plates and the cryogenic process was performed in the modified cylinder-shaped equipment that was equipped with a Teflon tube inserted into the sealed steel chambers [11]. The Teflon tube was adjusted to allow the mobility of liquid nitrogen in the steel chamber.

After the cryogenic SMAT process, the cross-sectional samples were polished and etched in a ferric chloride, hydrochloric acid and anhydrous ethanol solution for microstructure analysis. The microstructure of Cu–Zn alloys was characterized by optical microscopy (Leica DM5000) and scanning electron microscopy (SEM, TESCAN VEGA 3). Optical imaging of etched samples was used to assess the grain size and defect morphology. Electron backscatter imaging under SEM was used to analyze the failure surfaces and the microstructure of matrix and deformed layer. The microhardness of SMAT sample was performed on a cross-sectional sample by a Viker microhardness tester with a load of 50 g and a loading time of 15 s. In order to exclude the interaction between tested points during measurements, neighboring indentations from the treated surface to the interior were separated by 30 µm. The reported results are the average of all data sets. For tensile testing, all SMAT samples were cut into dog-bone shaped specimens with a gauge length of 15 mm, a width of 5 mm and a thickness of 0.6 mm. Tensile tests were performed at room temperature using a Shimazu Universal Tester at a strain rate of $1.0\times10^{-4}\ s^{-1}$. After failure, the failure surfaces were analyzed by SEM.

3. Results and discussion

Fig. 1a and b shows cross-sectional optical microscopy images of the cryogenic SMAT and untreated Cu–30%Zn alloy surface after etching. By comparing Fig. 1a and b, it can be clearly seen that after the SMAT process the microstructure of the sample is significantly changed and grains are obviously refined. During cryogenic SMAT processing, the surface of the sample was multidirectionally impacted at high strain rates and severe plastic strain was induced into sample [11]. Because of the different strains with distance from the treated surface into matrix, the grains were refined to various degrees, which lead to the formation of a gradient structure. Fig. 1b shows the optical microscopy image of the annealed and pre-SMAT sample, where more coarse grains are seen.

Fig. 2 shows SEM images of the etched sample cross-sections of sample prepared by cryogenic SMAT processing for 5 min. Microscopic observations have confirmed that the surface layer of the cryogenic SMAT sample is free of cracks or porosity. These micrographs illustrate the change in microstructure (grain size) as a function of depth from the SMAT surface. As shown in Fig. 2b, microstructure morphology of the treated surface layer differs significantly from the matrix, in which severe plastic deformation can be identified to 150 µm below the top surface layer. In the high magnification of selected region, the SMAT surface has a fine-grained layer nearly 10 µm in thickness (Fig. 2c). As shown in Fig. 2a, there could be seen many blocks filled with parallel and straight strips (deformation twins) and their density increased at depths below 20 µm. Formation of this gradient structure can be understood in terms of the strain and strain rate distribution during the cryogenic SMAT process. The topmost surface layer undergoes plastic deformation with the largest strains and strain rates [13]. Further, the low deformation temperature caused deformation twinning to dominate the plastic deformation in this regime [11]. Further plastic deformation generates the formation of micron-sized grains via shear banding and fragmentation of the twin bundles [13].

The variation of microhardness along the depth from the treated surface layer was measured in a cross-sectional sample after cryogenic SMAT, as shown in Fig. 3. In the topmost surface fine-grained layer of SMAT Cu–30%Zn, Cu–20%Zn and Cu–10%Zn alloys, the hardness reaches a maximum value of 1.76 GPa, 1.55 GPa and 1.36 GPa, respectively. For comparison, microhardness measurements have also been performed through the cross-section of annealed samples without cryogenic SMAT. For the annealed Cu–30%Zn, Cu–20%Zn and Cu–10%Zn alloys, the distributions of the local hardness remain more homogeneous: throughout the thickness of these specimens a constant hardness of 0.93 GPa, 0.86 GPa and 0.75 GPa are obtained, respectively. As depicted in Fig. 3, the microhardness of surface fine-grained layer is approximately 2 times higher than the initial hardness of the coarse-grained samples. In addition, it can be observed that the cryogenic SMAT process considerably improves the local hardness of these coarse-grained matrix sections of SMAT samples to 1.40 GPa, 1.15GPa and 1.11 GPa at a depth of about 300 µm, respectively. These values are approximately 1.5 times higher than the hardness of the annealed samples, and can be explained as the high work hardening occurring during the cryogenic SMAT process [11].

Fig. 3 shows that an obvious increment in microhardness occurs in surface layer of Cu–Zn alloys treated by means of cryogenic SMAT. But the increasing magnitude varies from the three alloys with different zinc content under the same conditions of cryogenic SMAT. An obvious increase in microhardness from the core to the surface of cryogenic SMAT samples seems to follow the grain refinement observed by SEM (Fig. 2). For the SMAT Cu–Zn samples, the reasons for such a different increment of microhardness after cryogenic SMAT can be partly attributed to the differences of refining mechanisms for alloys with varied lattice structures and SFEs [1,14,15]. Dislocation activities and plastic deformation behaviors in metals and alloys depend strongly on the lattice structure and the SFE [1]. For example, in those face-centered cubic materials with low SFEs, dissociated dislocations and deformation twins are promoted and the cross-slip of dislocations is thereby prohibited, which resulted in less recovery and more grain refinement during plastic deformation [16]. While for those with high SFEs, full dislocations have more chance to cancel each other since they are difficult to be dissociated. Dynamic