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Superior room temperature ductility of magnesium dilute binary alloy via grain boundary sliding

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ABSTRACT

Fine-grained Mg-Xat.%Bi dilute binary alloys having different concentrations of bismuth element were produced by conventional extrusion process. The ductility decreased with increasing bismuth addition; however, the Mg-0.3 at.%Bi alloy containing binary phase particles exhibited an elongation-to-failure in tension of 170% even at a strain rate of 1×10^{-3}/s at room-temperature. This superior mechanical property results from grain boundary sliding, which is closely related to equilibrium grain boundary structures. This ductility has never been observed in any other magnesium alloys and the temperature of $0.32T_m$ for obtaining the present superplastic-like behavior is the lowest among the conventional metallic materials.

Magnesium and its alloys, which have the lowest density among conventional metallic materials, have attracted significant attention as light-weight metallic materials; however, their application is still limited. The ductility, i.e., the elongation-to-failure, of magnesium and its alloys is poor as compared to that of the other metals, because of its hexagonal closed packed structure. There are two well-known strategies to resolve this serious issue. The first method is the texture control (basal plane distribution) by thermo-mechanical process [1,2]. For example, equal-channel-angular extruded (ECAE-ed) magnesium alloys show elongation-to-failure in tension of about 40%, which is at least twice that of the conventional magnesium alloys [1]. Since the ECAE-ed alloy has a basal plane tilt of approximately 45° against the applied stress direction, dislocations on the basal plane readily slip under low applied stress, in agreement with the Schmid law. Another method is the activation of non-basal dislocation slips by grain refinement or by specific alloying element addition [3–6]. The ductility tends to increase with finer grained structures, because of enhancement of grain boundary (GB) compatibility operation [3]. Specific alloying elements, such as rare-earth elements, are recognized for their role in reducing the difference between basal and non-basal resolved shear strength [4–6].

These methods mentioned above have been focused on controlling of dislocation slips. Grain boundary sliding (GBS) is also another essential plastic deformation mechanism for metallic materials, especially at elevated temperatures [7]. Several papers have pointed out a partial occurrence of room-temperature GBS for pure magnesium [8–12]. This suggests that GBS is another promising answer to solve the issue of ductility improvement, by changing from dislocation slip control. Interestingly, current studies have reported that fine-grained pure magnesium shows a large elongation-to-failure in tension of 230%, and Hall-Petch law breakdown occurs even in several micron-orders of grain size, due to contribution of GBS [9]. Systematic investigations have revealed the effect of alloying elements on ductility of magnesium binary alloys via GBS [13]. Most of the alloying elements have a characteristic of GBS suppression, except for only two alloying elements, i.e., manganese and lithium, which bring about enhancement of GBS. These GBS inhibition/promotion behaviors result from GB segregation; nevertheless, our further recent studies have found out a possibility to develop a highly deformable magnesium alloy through not GB segregation but GB structural control, i.e., equilibrium GB structures [14]. Even under compressive stress state, which generates deformation twinning readily, this Mg-Bi alloy exhibits an excellent compressive deformability in high-strain rate regimes, similar to the feature of aluminum alloys. In this study, we have investigated the mechanical properties and its deformation mechanism in further detail using several Mg-Bi alloys. We have also considered the segregation/non-segregation effect on these characteristics by comparison with those of the alloy (Mg-Mn alloy) having GB segregation.

Several extruded Mg-Xat.%Bi (X = 0.3, 0.6 and 1.0) and Mg-0.3 at.% Mn binary alloys were used in this study. The chemical compositions of the major alloying element and some impurities in these binary alloys are listed in Supplementary Table S1. These binary alloys, which were produced by conventional casting method, were annealed at 773 K for 2 h, and then were extruded to control the grain structures, i.e., grain refinement, at various temperatures between 378 and 483 K, as listed in Supplementary Table S2. In the case of Mg-0.3Bi alloy, the same cast/annealed alloy was used, but low temperature extrusion was performed to obtain finer grained structures. Hereafter, the alloy having an average

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grain size, d, of 1–2 μm is denoted as "fine-grained" alloy. A commercial extruded magnesium alloy (Mg-3wt.%Al-1wt.%Zn; AZ31 alloy) was also used for comparison. This AZ31 alloy was also re-extruded at 483 K to control the grain structures, i.e., d = ~3 μm. All the extruded alloys were rod-shaped with a diameter of 8 mm (extrusion ratio of 25:1). The initial microstructures of these extruded alloys were observed by electron-back scattering diffraction (EBSD) method. The EBSD observations were made on the transverse-direction and the extrusion-direction. The phases of the fine-grained Mg-0.3Bi and Mg-1.0Bi alloys were identified by X-ray diffraction (XRD) method using Cu-Kα radiation. The measurement plane was normal to the extrusion-direction. Microstructural observations using transmission electron microscopy (TEM) and high-resolution election microscopy (HREM) were performed on selected alloys. As for the extruded Mg-0.3Mn alloy, the initial microstructures using EBSD, TEM and three-dimensional atom probe have been already reported in our previous studies [13]. In brief, the extruded Mg-0.3Mn alloy (d = 2.8 μm) had a basal texture and segregation of manganese at GBs.

Tensile tests were carried out to assess the mechanical properties and its deformation mechanism. The initial strain rates were set at 1×10^{-2}, 10^{-3}, 10^{-4} and 10^{-5}/s. All the extruded Mg-Bi, Mg-Mn and AZ31 alloys were tested at room-temperature (298 K), and specific alloys (Mg-0.3Bi and Mg-0.3Mn alloys having d = ~3 μm) were carried out at 273 and 323 K at the initial strain rate of 1×10^{-5}. The tensile specimens, which were made by machining parallel to extrusion direction, had a diameter of 2.5 mm and a gauge length of 10 mm. After room-temperature tensile test, cross-section and deformed surface of the fine-grained Mg-0.3Bi alloy, i.e., the ruptured sample at the strain rates of 1×10^{-4} and 10^{-5}/s, were observed by scanning electron microscopy (SEM).

The initial microstructure of the fine-grained Mg-0.3Bi alloy observed by EBSD method is shown in Fig. 1(a). The inverse pole figure image demonstrates that the microstructures consist of recrystallization and the average grain size is 1.2 μm. EBSD images of the other alloys are shown in Supplementary Fig. S1. The average grain sizes measured from EBSD analysis are provided in Supplementary Table S2. All of the extruded alloys are found to have recrystallized structures without any bimodal structures. Several Mg-Bi alloys have similar average grain sizes of 1–2 μm. The average grain size of the AZ31 and Mg-0.3Bi alloys is obtained to be approximately 3 μm, which is close to that of the extruded

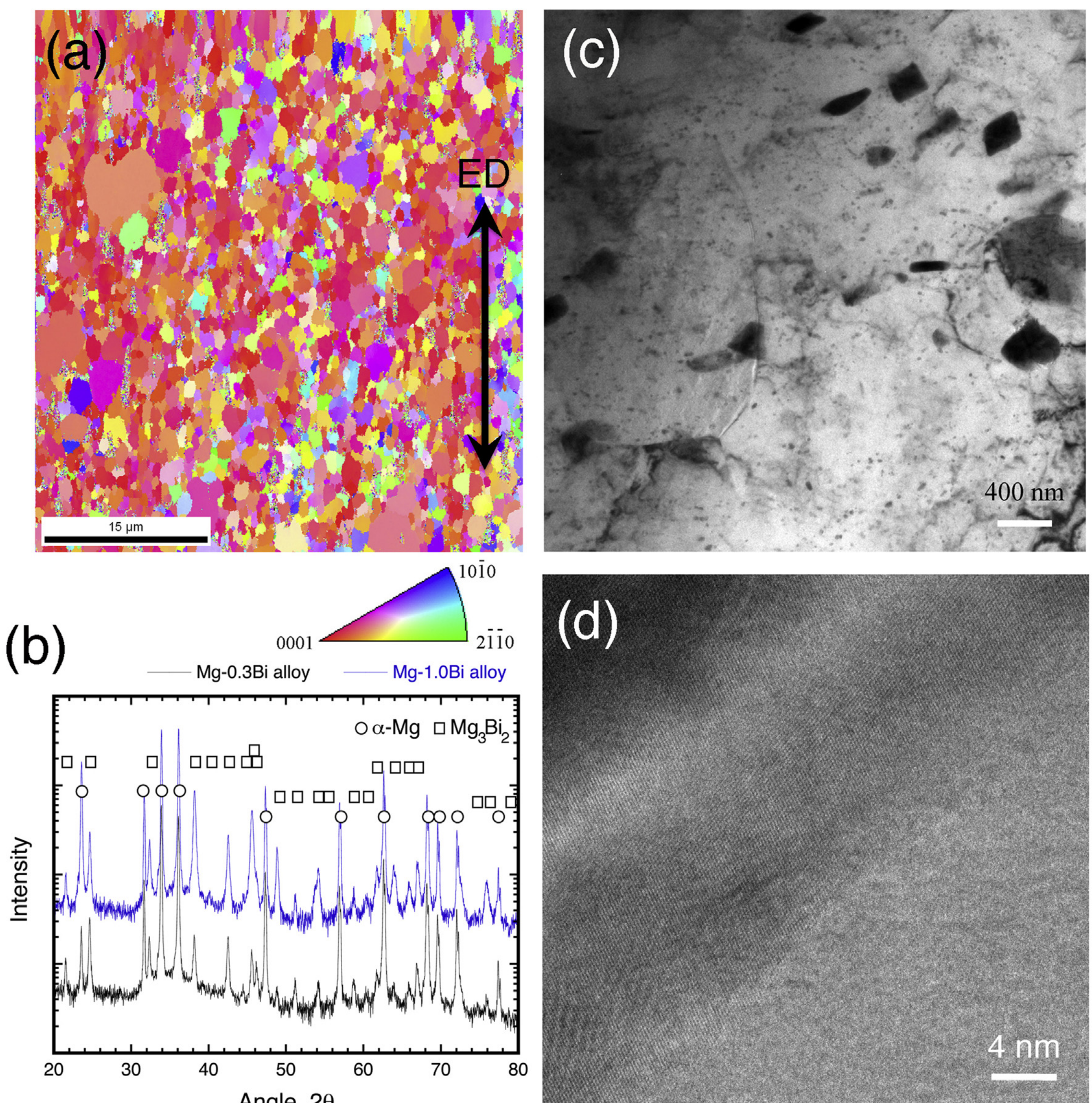

Fig. 1. The initial microstructural observations of the extruded Mg-Bi alloy; (a) inverse pole figure image of the fine-grained Mg-0.3Bi alloy, (b) XRD pattern of the fine-grained Mg-Bi alloys, (c) TEM image and (d) HREM image in vicinity of grain boundary for the fine-grained Mg-0.3Bi alloy. ED in Fig. (a) indicates extrusion-direction.