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High-strain-rate superplasticity of fine-grained Mg–6Zn–0.5Zr alloy subjected to low-temperature indirect extrusion

Beomcheol Kim [a,1], Jong Chan Kim [a,1], Sooseok Lee [a], Ki-Suk Lee [a], Jung Gu Lee [b,*], Sung Soo Park [a,*]

[a] School of Materials Science and Engineering, Ulsan National Institute of Science and Technology, Ulsan 44919, Republic of Korea
[b] School of Materials Science and Engineering, University of Ulsan, Ulsan 44610, Republic of Korea

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ABSTRACT

A commercial Mg–6Zn–0.5Zr alloy was subjected to low-temperature indirect extrusion for grain refinement and the tensile properties of the extruded alloy at 250 °C were investigated. After extrusion, the alloy showed finely recrystallized grains with an average size of 1.6 μm. High-strain-rate superplasticity was observed in the fine-grained alloy, which exhibited a tensile elongation of up to 800% at a strain rate of 0.01 s^{-1}. Experimental results demonstrating the occurrence of grain boundary sliding during the high-strain-rate superplastic deformation are presented.

Developing Mg alloy extrusions with more competitive mechanical properties is necessary to support the growing need for various lightweight components in the automotive industry [1]. Commercial Mg alloy extrusions, however, generally suffer from insufficient strength, which mainly results from a coarse-grained microstructure associated with hot processing conditions [2]. This drawback in the mechanical properties inevitably limits the applicability of extruded Mg alloys to various weight-sensitive applications. One possible method to overcome this issue in Mg alloys is to reduce the processing temperature to a critical level below which grain growth is readily retarded, thereby heightening the strength of the Mg alloys in the extruded state.

It has recently been shown that the microstructure of Mg alloys can be effectively controlled by the application of a low-temperature indirect extrusion process specially designed to enable artificial cooling during indirect extrusion [3,4]. It has been demonstrated that this novel extrusion process effectively provides grain refinement for Mg alloys, resulting in considerably increased strength levels at room temperature [3–6]. In fact, grain size is considered a crucial factor affecting the high-temperature plasticity of metallic materials [7]. Fine-grained Mg alloys processed by this novel extrusion process are thus expected to have enhanced high-temperature plasticity compared to that of samples subjected to a typical extrusion process without artificial cooling. In this study, a commercial Mg–6Zn–0.5Zr (ZK60) alloy was subjected to a low-temperature indirect extrusion process for grain refinement and the tensile properties of the fine-grained alloy at 250 °C were investigated.

The analyzed composition of the ZK60 alloy was Mg–5.7 wt% Zn–0.54 wt% Zr. A cylindrical extrusion billet was prepared by induction melting in a graphite crucible under an inert atmosphere with a CO_2 and SF_6 mixture and subsequent pouring into a steel mould pre-heated to 200 °C. The cast billet was homogenized at 440 °C for 4 h, followed by water quenching. The billet dimensions were 80 mm in diameter and 150 mm in length. An indirect extrusion experiment was implemented at an initial billet temperature of 250 °C, a ram speed of 1.3 mm s^{-1}, and an extrusion ratio of 25. After extrusion was initiated, cooling media consisting of water and air were provided through inlets on the stem surface. These cooling materials were transferred through holes inside the stem and then were directly sprayed onto the extruded rod at the die exit, as schematically shown in Fig. 1a. The water feeding rate and air pressure were 1.8 l min^{-1} and 0.8 MPa, respectively. During extrusion with the artificial cooling procedure, the temperature measured at the die exit was 180 °C.

Microstructural examinations were conducted on midsections parallel to the extrusion direction (ED) by optical microscopy, electron backscatter diffraction (EBSD), and transmission electron microscopy (TEM). Grain size was measured by using a linear intercept method; $d = 1.74 \times L$, where d is the grain size and L is the linear intercept size. High-temperature tensile tests were carried out at 250 °C under various initial strain rates in a range of 0.001–0.1 s^{-1}. Round tensile specimens with a 20 mm gage length and a 5 mm gage diameter were used for tensile tests; specimens were stabilized for 10 min prior to testing. Flow stress was determined at a tensile strain of 0.1 from true stress-strain curves. Using atomic force microscopy (AFM), the

* Corresponding authors.
E-mail addresses: sspark@unist.ac.kr (S.S. Park), jglee88@ulsan.ac.kr (J.G. Lee).
[1] The authors contributed equally to this work.

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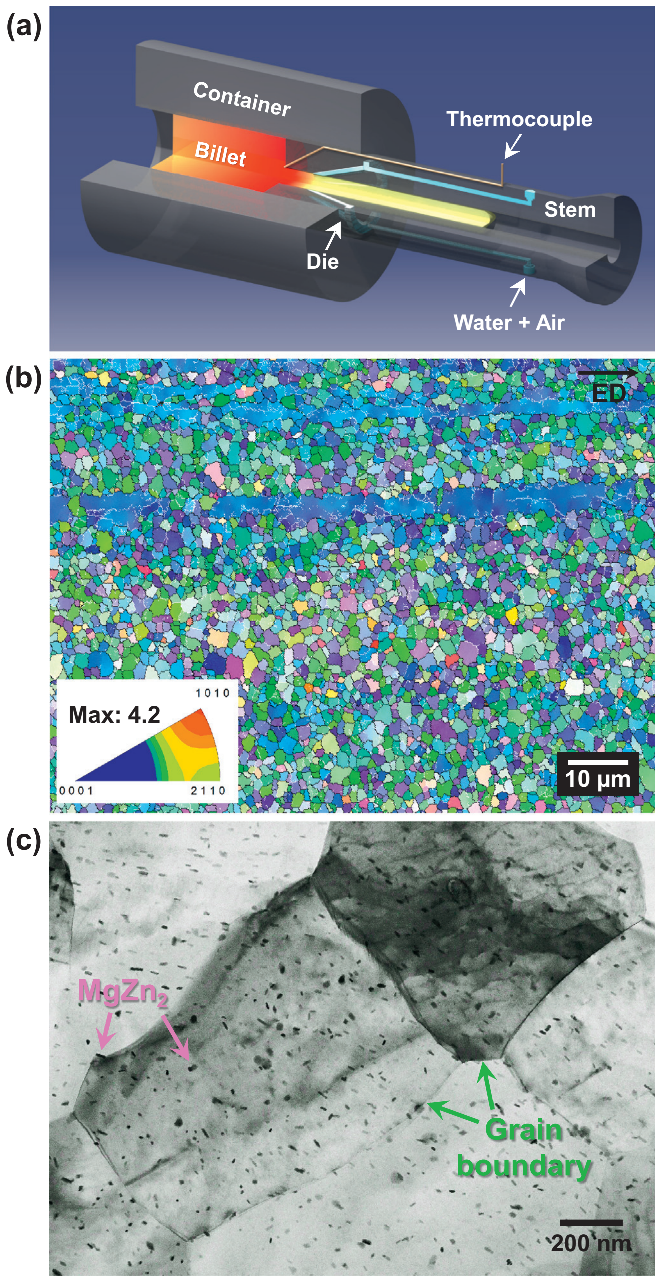

Fig. 1. (a) Schematic diagram of a low-temperature indirect extrusion process capable of artificial cooling with the (b) EBSD orientation map, inverse pole figure, and (c) TEM micrograph of the ZK60 alloy processed by low-temperature indirect extrusion. The EBSD orientation map and inverse pole figure refer to the ED.

extent of grain boundary sliding (GBS) was estimated from the measurement of offsets perpendicular to the specimen surface after a true strain of 0.2. A flat tensile specimen with a 5 mm gage width, a 2 mm gage thickness, and a 20 mm gage length was used for the AFM measurement after surface polishing

Fig. 1b provides an EBSD orientation map of the ZK60 alloy processed by low-temperature indirect extrusion utilizing artificial cooling. The map reveals fine α-Mg grains formed via dynamic recrystallization (DRX) during extrusion. In addition, relatively coarse grains elongated along the ED, representing incomplete DRX, are found to exist with the fine recrystallized grains. The average area fraction of the coarse elongated grains and the average size of the recrystallized grains were measured and found to be 16.9% and 1.6 μm, respectively. The extruded alloy exhibited a texture that can be typically observed in extruded Mg alloys [3–6,8]. The bright-field TEM micrograph shown in Fig. 1c indicates that the extruded ZK60 alloy has $MgZn_2$ precipitates with sizes under ~50 nm within the α-Mg matrix as well as at the grain boundaries, as was similarly observed in extruded ZK60 alloys [9–11]. Misorientation analyses by EBSD and TEM proved that most of the fine α-Mg grains have high-angle boundaries. The fine-grained ZK60 alloy showed excellent tensile properties at room temperature, exhibiting yield and ultimate strengths of 298 and 348 MPa, respectively, with an elongation-to-failure of 23% [4].

To evaluate the tensile properties of the fine-grained alloy at elevated temperature, tensile tests were performed at 250 °C at different initial strain rates in a range of 0.001–0.1 s^{-1}. Fig. 2 shows the changes in the tensile elongation and flow stress of the extruded alloy as a function of the strain rate. As indicated in Fig. 2a, elongation tends to decrease as the strain rate increases. However, there appears to be a large difference in elongation between strain rates of 0.01 and 0.02 s^{-1}. Large elongation values of 800–900% were obtained in the relatively slow strain rate

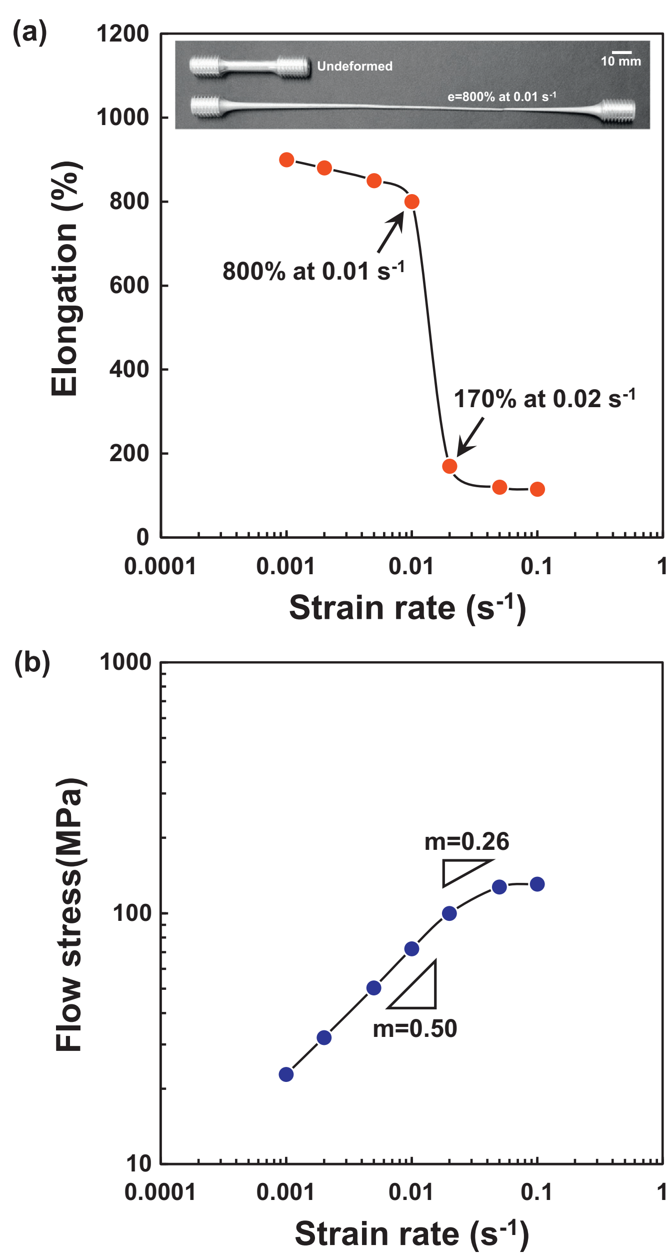

Fig. 2. Variations in (a) tensile elongation and (b) flow stress of the extruded ZK60 alloy at 250 °C as a function of strain rate.