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Grain refinement and improved tensile properties of Mg–3Al–1Zn alloy processed by low-temperature indirect extrusion

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The microstructure and tensile properties of a Mg–3Al–1Zn alloy processed by low-temperature indirect extrusion utilizing artificial cooling were investigated. Grain refinement from 5.5 to 1.8 μm was attained by the application of artificial cooling, resulting in an increase in yield strength of as much as 50 MPa at room temperature as well as enhanced plasticity with tensile elongations of 200–320% at strain rates in the range of 3.3×10^{-5}–1.0×10^{-4} s^{-1} at 150 °C.

Keywords: Magnesium alloy; Indirect extrusion; Artificial cooling; Grain refinement; Superplasticity

Development of high-strength Mg alloy extrusions is required to support the growing need for lightweight components in the automotive industry [1]. Extruded Mg alloys, however, generally suffer from low strength, which mainly results from the coarse-grained structure associated with high-temperature processing [1–3]. The poor mechanical properties of Mg alloy extrusions limit their applicability. One possible method to overcome this issue in Mg alloys is to use low-temperature extrusion processing, which can suppress excessive grain growth, thereby improving the strength as well as the plasticity of extrusions [4]. The authors have recently devised a novel low-temperature indirect extrusion process capable of extruding Mg alloys at temperatures <200 °C by means of artificial cooling. In this study, we report the effects of artificial cooling during indirect extrusion on the microstructure and tensile properties of an extruded commercial Mg–3Al–1Zn (AZ31) alloy.

The analyzed composition of the AZ31 alloy used here was Mg–2.9 wt.% Al–0.65 wt.% Zn–0.31 wt.% Mn. Details of the billet-casting procedure have been described elsewhere [3]. After casting, the alloy was homogenized at 400 °C for 10 h, followed by air-cooling. The dimensions of the billet were 80 mm in diameter and 200 mm in length. Indirect extrusion experiments were implemented at an initial billet temperature of 250 °C, a ram speed of 1.3 mm s^{-1}, and an extrusion ratio of 25. In this study, artificial cooling was selectively applied to achieve low-temperature extrusion processing, as schematically shown in Figure 1. After extrusion was initiated, cooling media consisting of cold water and air were provided through inlets on the stem surface. The cooling media were transferred through holes inside the stem and were then directly sprayed onto the extruded rod at the die exit. The water feeding rate and air pressure were 1.7 l min^{-1} and 0.8 MPa, respectively. The die exit temperatures of the alloys subjected to extrusion with and without artificial cooling were 180 and 292 °C, respectively. Microstructural and textural examinations were conducted on the midsections perpendicular to the extrusion direction (ED) by optical microscopy, electron backscatter diffraction (EBSD) and X-ray diffraction (XRD) in the back-reflection mode with Cu K_α radiation. Tensile properties were measured at an initial strain rate of 1.0×10^{-3} s^{-1} at room temperature and at initial strain rates of 3.3×10^{-5}–3.3×10^{-3} s^{-1} at 150 °C, respectively, using round tensile specimens with a gage length of 20.0 mm and a gage diameter of 5.0 mm. The flow stress at 150 °C was determined at a true strain of 0.1.

Figure 2 shows optical micrographs of the AZ31 alloys extruded with and without artificial cooling,

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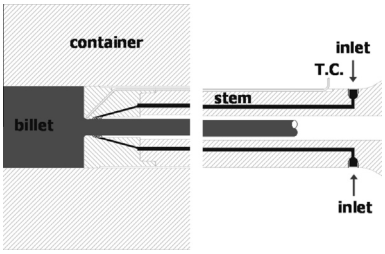

Figure 1. Schematic diagram of an indirect extrusion process capable of artificial cooling.

respectively. It can be clearly seen that artificial cooling has a significant effect on grain refinement. The average linear intercept grain sizes are 1.8 and 5.5 μm for the alloys extruded with and without cooling, respectively. The alloy with cooling reveals the presence of relatively coarse grains, suggesting that dynamic recrystallization (DRX) remains incomplete for some grains after extrusion processing is complete. It is probable that DRX, being a diffusion-controlled process, becomes more sluggish as the processing temperature decreases [5]. The grain size of the AZ31 alloy with cooling in this study is comparable to the grain sizes of AZ31 alloys subjected to severe plastic deformation (SPD) processes such as equal-channel angular pressing (ECAP) [6–10] or accumulative roll bonding [11]. It should be noted here that the low-temperature indirect extrusion applied in this study does not need repetitive deformation procedures, which are required in SPD processes, indicating that such grain refinement can be more efficiently achieved by the former method.

Textures of the extruded alloys measured by XRD are also presented in Figure 2 in the form of inverse pole figures, which refer to the ED. They show a fiber texture in which basal poles are preferentially perpendicular to the ED and the maximum intensity is centered at $[1\,0\,\bar{1}\,0]$, which is typical of extruded Mg alloys [12]. The alloy subjected to cooling displays a stronger texture than that without cooling, exhibiting maximum intensities of 3.8 and 2.8, respectively. Such a relatively strong texture in the alloy with cooling can be attributed to the presence of the incompletely recrystallized coarse grains, which retain strong fiber texture [13].

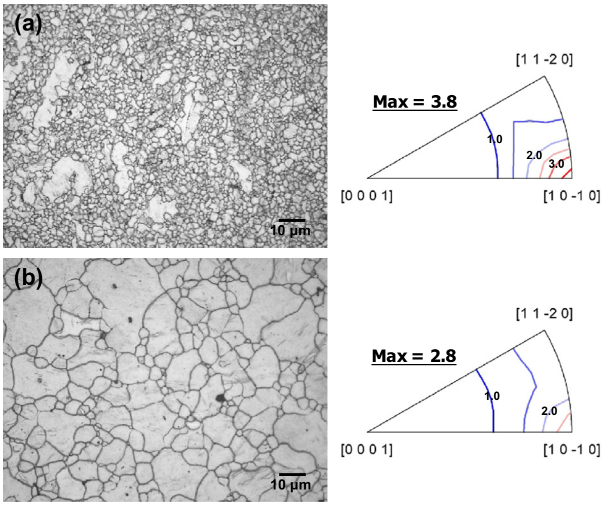

Figure 2. Optical micrographs and inverse pole figures of the AZ31 alloys extruded (a) with and (b) without artificial cooling.

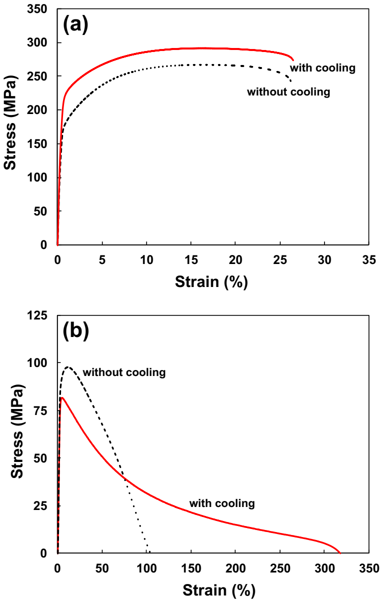

Figure 3. (a) Engineering stress–strain curves of the AZ31 alloys with and without artificial cooling at (a) room temperature and (b) 150 °C.

Figure 3a shows the tensile stress–strain curves of the extruded alloys at room temperature. The alloy with cooling shows higher yield and ultimate strengths than the alloy without cooling. The yield and ultimate strengths of the former are 220 and 292 MPa, respectively, whereas they are 170 and 267 MPa for the latter. Interestingly, the two extruded alloys reveal an equivalent elongation value of 26%, despite their considerable difference in strength. This indicates that the artificially cooled alloy has a better combination of strength and ductility than the typically extruded alloy without cooling at room temperature.

Tensile properties of extruded alloys at an elevated temperature of 150 °C were also evaluated at strain rates in the range of 3.3×10^{-5}–$3.3 \times 10^{-3}\ \mathrm{s}^{-1}$. As shown in Figure 3b and Table 1, the extruded alloys show differences in both flow stress and elongation, which tend to increase as the strain rate decreases. The largest tensile elongation obtained for the alloy with cooling over the test regime is 320%, whereas that of the alloy without cooling is only 105%. It is interesting that the fine-grained AZ31 alloy extruded with artificial cooling exhibited superplastic elongation exceeding 300% at a low temperature of 150 °C, where superplastic properties have rarely been reported in Mg alloys [7,14,15].

To observe microstructural and textural changes occurring during the tensile test at 150 °C, EBSD orientation maps were obtained from the grip and gage sections of tensile samples after tensile testing at a strain rate of $3.3 \times 10^{-5}\ \mathrm{s}^{-1}$, as shown in Figure 4. The orientation maps show microstructural refinement in the gage sections after tensile deformation, which can be attributed to the occurrence of DRX during the tensile test. Although grain sizes in the grip sections remain nearly