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Effect of billet diameter on hot extrusion behavior of Mg–Al–Zn alloys and its influence on microstructure and mechanical properties

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ABSTRACT

The effect of the initial billet size on the microstructural evolution and tensile properties of extruded AZ61 and AZ91 Mg alloys was investigated using homogenized billets with diameters of 50 and 80 mm. All the extruded alloys exhibit a bimodal structure consisting of fine dynamically recrystallized (DRXed) grains with numerous precipitates and relatively coarse DRXed grains with few precipitates. Although the size and hardness of the fine DRXed grains do not vary with the billet size, using a smaller billet results in a significant reduction in the size and area fraction of coarse DRXed grains because of an increase in the quantity of precipitates. This increase in both the fraction of fine grains and the number of $Mg_{17}Al_{12}$ precipitates improves the tensile strength of the extruded alloys. This size effect can be attributed mainly to the increase in the strain rate with decreasing billet diameter, which promotes dynamic recrystallization and precipitation during extrusion. The effect of billet size is more pronounced in the AZ91 alloy, which has a high concentration of alloy elements, than in the AZ61 alloy.

1. Introduction

The low density and high specific strength of Mg alloys make them a preferred choice for use in the transportation industry, where weight reduction is a critical issue for improving fuel efficiency and decreasing greenhouse gas emissions. Extruded Mg alloys have been attracting significant attention in recent years because they have much higher mechanical properties than cast Mg alloys and consequently provide both a more effective weight reduction and greater safety of components; they are also easier to fabricate using a one-pass process and offer a greater diversity of shapes, such as sheets, rods, tubes, beams, and channels, compared to rolled products [1].

The microstructure and mechanical properties of extruded Mg alloys are known to depend strongly on both the microstructural characteristics of a billet before extrusion and the process variables during extrusion. For example, a finer-grained billet results in a considerable reduction in the area fraction of non-recrystallized grains, significantly improving the tensile ductility of the extruded Mg alloy [2]. Moreover, artificially formed twins/precipitates in the billet can also affect the dynamic recrystallization (DRX) behavior during hot extrusion, resulting in a great variation in the final microstructure and mechanical properties [3,4]. As the deformation temperature, ram speed, and/or extrusion ratio decrease, the strength of the extruded Mg alloys generally increases owing to a reduction in the size of the DRXed grains and/or an increase in the number of precipitates [5–8]. The die angle can also influence the microstructural inhomogeneity of the extruded Mg alloy owing to variation in the flow rate, deformation temperature, and effective strain near the work zone during extrusion [9].

The deformation behavior and mechanical properties of many engineering materials can vary with the size of the structural member [10–14]. In general, smaller structures have higher strength and lower ductility than larger ones under tensile deformation at room temperature (RT) [15]. Owing to this size effect, results from laboratory tests cannot be directly translated to actual structures. Accordingly, a physical understanding of the size effect is highly important for engineers who try to extrapolate experimental outcomes at the laboratory scale to structural components over a practical size range. Given that the size can affect not only the stress–strain response at RT but also the deformation behavior at high temperatures, the diameter of the billet used can also affect the microstructural evolution during extrusion, even if billets with

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the same microstructural states (e.g., chemical composition, grain size, and second phase) are subjected to extrusion under exactly identical conditions (e.g., temperature, ram speed, extrusion ratio, and die angle). For this reason, the microstructure, strength, and ductility of materials after extrusion can differ significantly from our expectations based on laboratory results when newly developed alloys are used in large-scale structural products. Therefore, it is necessary to investigate the effect of billet size on the extrusion behavior in order to use Mg alloys as structural components. However, despite extensive research into the effect of the microstructural features of the initial billet on extruded Mg alloys [2–4,16], there have been no in-depth studies examining the variation in the microstructure and mechanical properties of extruded Mg alloys according to the billet size. This study therefore systematically investigates the influence of the billet size on the hot deformation behavior during extrusion, such as DRX and dynamic precipitation (DP), as well as the resultant hardness and tensile properties.

2. Materials and methods

Commercial AZ61 (6.0 wt% Al, 1.0 wt% Zn, 0.2 wt% Mn, balance Mg) and AZ91 (9.0 wt% Al, 1.0 wt% Zn, 0.2 wt% Mn, balance Mg) alloys were used for this study, and cast billets were prepared according to a previously described procedure [3]. The as-cast billets were homogenized at 420 °C for 24 h and then water-quenched. These billets were machined to prepare samples for extrusion with diameters of 50 and 80 mm for the AZ61 and AZ91 alloys (hereafter denoted as AZ61-50, AZ61-80, AZ91-50, and AZ91-80, respectively). After preheating to 250 °C for 1 h, the billet samples were indirectly extruded at a temperature of 250 °C, a ram speed of 1 mm/s, and an extrusion ratio of 20, i.e., all the extrusions were conducted under the same process parameters (temperature, speed, and extrusion ratio). The die with an angle of 90° and container were preheated to the initial billet temperature of 250 °C to avoid temperature variation in the remaining billet during extrusion. No lubricant was used during extrusion because of the virtual absence of friction between the billet and the container walls during indirect extrusion [17]. After processing, all of the extruded materials were allowed to cool naturally in air. The actual temperature of the deformation zone during extrusion was measured using a thermocouple installed inside the die [5], and it was found to be ~290 °C because of the deformation heat generated by plastic deformation and friction during extrusion.

The microstructural characteristics of the homogenized billets and extruded bars were analyzed by optical microscopy and/or field emission scanning electron microscopy (FE-SEM). The electrical resistivity of the homogenized billets and extruded bars was measured using a previously described method [18] to quantitatively analyze the precipitates formed during extrusion. Hardness profiles extending from the center to the surface of the extruded bars were measured using a micro-Vickers hardness tester with a load of 200 gf and a dwell time of 10 s. Average hardness values were obtained from measurements at 20 different positions for each sample and region. The tensile properties of the extruded bars were measured at RT using an Instron 4206 universal testing machine with a strain rate of 1.0×10^{-3} s^{-1}. Dog-bone shaped (gage section: ϕ6 mm × 25 mm) specimens were used for tensile testing.

3. Results

3.1. Microstructural characteristics

The optical and SEM micrographs of the homogenized billets in Fig. 1 reveal that both the AZ61 and AZ91 alloys have almost the same average grain size, ~420 μm, and the $Mg_{17}Al_{12}$ secondary phase that is formed during solidification is fully dissolved by homogenization in both alloys. Although thermally stable Al–Mn phases, such as Al_8Mn_5 and $Al_{11}Mn_4$, remain after homogenization (Fig. 1c and d), they only have a negligible effect on the hot extrusion behavior because of their limited amount (area fraction: 0.40% and 0.46% for AZ61 and AZ91, respectively). This microstructural state with no $Mg_{17}Al_{12}$ phase and a small quantity of Al–Mn particles in the homogenized billets is consistent with previous observations of Mg-8Al-0.5Zn (wt.%) [19] and Mg-8.8Al-0.67Zn (wt.%) [20] alloys.

The longitudinal cross-sectional microstructures of the extruded alloys (Fig. 2) show that all the alloys exhibit a nearly fully DRXed structure with only a small quantity of elongated non-DRXed grains (area fraction of non-DRXed grains: 2.6%, 3.0%, 5.9%, and 5.7% for AZ61-50, AZ61-80, AZ91-50, and AZ91-80, respectively). Note that the DRXed structure is composed of coarse DRXed grains with few precipitates (ppt-scarce region) and relatively fine DRXed grains with numerous precipitates (ppt-rich region). This inhomogeneous distribution of precipitates can be attributed to microsegregation of the Al dissolved within the α-Mg matrix of the homogenized billet [21]. Fig. 2 shows that the area fraction of the ppt-rich region is much higher in the AZ91 alloys (Fig. 2c and d) than in the AZ61 alloys (Fig. 2a and b). According to the variation in the Al solubility limit with the temperature for the equilibrium state of the Mg-1Zn-0.2Mn (wt.%) alloy calculated using the FactSage program (Fig. 3), the Al solubility at the homogenization temperature of 420 °C (9.92 wt%) is greater than the Al content of AZ61 and AZ91 alloys (6 and 9 wt%, respectively), resulting in complete dissolution of the $Mg_{17}Al_{12}$ phases during the homogenization treatment (Fig. 1). As the Al solubility decreases considerably to 5.35 wt% at 290 °C, which is the actual temperature in the deformation zone during extrusion, any amount of Al greater than this solubility (0.65 and 3.65 wt% for AZ61 and AZ91 alloys, respectively) will be precipitated as $Mg_{17}Al_{12}$ particles during extrusion, producing more precipitates in the AZ91 alloys than in the AZ61 alloys.

3.2. Precipitate analysis

In the AZ61 alloy, the area fraction of the ppt-rich region shows almost no variation with the initial billet size (Fig. 2a and b), whereas it decreases considerably as the billet size increases from 50 to 80 mm in the AZ91 alloy (Fig. 2c and d). To quantitatively investigate the precipitated $Mg_{17}Al_{12}$, the electrical resistivity of the homogenized and extruded samples was measured. As shown in Fig. 4a, the electrical resistivity of the homogenized samples is much higher in the AZ91 alloy (171.6 nΩm) than in the AZ61 alloy (135.1 nΩm), indicating that the AZ91 alloy has a more supersaturated Al content in the α-Mg matrix. Given that crystal defects and precipitates have a negligible effect on the electrical resistivity of extruded Mg alloys [22], a smaller electrical resistivity in the extruded sample than in the homogenized sample can be attributed to the precipitation of $Mg_{17}Al_{12}$. For the AZ61 alloy, the electrical resistivity decreases slightly, from 135.1 to 131.4 and 131.6 nΩm, whereas in the AZ91 alloy, it decreases significantly, from 171.6 nΩm to 141.2 and 147.7 nΩm (Fig. 4a). This indicates that much more $Mg_{17}Al_{12}$ is precipitated in the AZ91 alloy during extrusion, which agrees well with the SEM images in Fig. 2 and the Al solubility variation in Fig. 3. By using the fact that a decrease in electrical resistivity of 3.99 nΩm in the Mg–Al–Zn alloy corresponds to the formation of 1 wt% $Mg_{17}Al_{12}$ [23], the quantity of $Mg_{17}Al_{12}$ precipitates in each of the extruded alloys is calculated, as shown in Fig. 4b. The results reveal that a smaller AZ61 billet yields a slightly higher quantity of $Mg_{17}Al_{12}$ precipitates than a larger