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Microstructure and mechanical properties of Mg –2Gd –3Y –0.6Zr alloy upon conventional and hydrostatic extrusion

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ABSTRACT

The Mg–12Gd–3Y–0.6Zr (wt. %) alloy was subjected to conventional and hydrostatic extrusion in two subsequent steps. The best combination of mechanical properties (strength and ductility) was achieved by RT hydrostatic extrusion following conventional extrusion at 430 °C, with the ultimate tensile strength (UTS), tensile yield strength (TYS) and elongation being 485 MPa, 413 MPa and 5.2% at room temperature. The texture results of extruded rods indicate that the *c*-axis of most grains was aligned preferentially perpendicular to the extrusion direction, forming a typical extrusion Mg fiber texture.
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1. Introduction

Magnesium and its alloys have increasingly attracted scientific interest for potential applications in the aerospace and transportation industries due to their low density and high specific strength, as well as some environment-friendly characteristics. Addition of rare earth (RE) elements to Mg is an effective way to achieve excellent mechanical properties combined with good ductility [1–3]. Recently, some works focusing on the development of high strength Mg alloys [4–6] reported that precipitation-hardenable Mg–RE–Zn or Mg–Gd–Y alloys are particularly promising due to their higher strength and superior creep resistance compared to conventional Mg alloys [7–11]. The tensile strength (UTS) of conventionally extruded Mg alloys reported so far lies between 300–450 MPa [6,12,13]. Achieving higher tensile strengths exceeding 500 MPa require non-conventional extrusion techiques, such as hydrostatic extrusion.

Extrusion at elevated temperatures (T>300 °C) is usually accompanied by dynamic recrystallization (DRX) and grain growth. It is therefore desirable to extrude at room temperature in order to reduce energy consumption and inhibit grain growth to maintain a fine grained microstructure. Hydrostatic extrusion (HE) became of particular interest for processing Mg alloys, due to its technical and economical advantages in the production of wrought structural components. During hydrostatic extrusion, the billet is forced through the die by means of equivalent fluid pressure. This eliminates any frictional force between the billet and its container, reducing all shear stresses near the die entrance. In almost all of the previous studies dealing with hydrostatic extrusion, cast material was used as billets, e.g. [14–16]. In this paper, we combine two different extrusion techniques to investigate the microstructure and mechanical properties of a high strength GW123 magnesium alloy.

2. Experimental procedure

The Mg–12Gd–3Y–0.6Zr (wt.%) (GW123) alloy was prepared using high purity (99.9%) Mg, Mg–20%Y, Mg–20%Gd and Mg–30%Zr master alloys in a mild steel crucible under protective gas atmosphere (SF_6 and CO_2). The ingots of diameter 180 mm were homogenized at 525 °C for 10 h and air-cooled afterwards. Conventional hot extrusion was carried out at 430 °C with extrusion ratio of 16:1. Hydrostatic extrusion was performed at room temperature with extrusion ratio of 16:1 using the previously extruded rods as billets. Metallographic sample preparation for microstructure and texture investigations is referred to in Ref [17]. Thin foils for transmission electron microscopy (TEM) observation were produced by ion mill polishing and examined in a high resolution TEM (JEM3010). Room temperature tensile testing was carried out on a CSS-44100 universal testing machine at a crosshead speed of 2 mm/min. The tensile gage was 67 mm in length and 5 mm in diameter. Each test was repeated three times and average stress-strain data was calculated. Micro-hardness was carried out by Vickers hardness tester. The test load and holding time were 25 g and 15 s, respectively. At least 10 points were measured to ensure statistical sufficiency. XRD texture measurements using the back reflection mode were performed on a Bruker D8 Discover with Cu-Kα radiation at 40 kV and 30 mA.

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3. Results and discussion

3.1. Microstructure development

Fig. 1 shows the microstructure of GW123 alloy upon conventional and upon subsequent hydrostactic extrusion. After conventional hot extrusion, most of the original coarse grains observed in the homogenized cast condition (not shown here) were transformed into fine equiaxed grains associated with the occurrence of DRX. In addition to the fine microstructure, a good proportion of coarse grains was visible, which altogether yielded a bimodal grain size distribution (Fig. 1a). Interestingly also, no mechanical twinning was observed. As shown in Fig. 1b, the microstructure was significantly refined during cold hydrostatic extrusion. Grain boundaries are very difficult to recognize due to large strain accumulation. The average grain size in both extruded conditions were 35 μm and 4 μm, respectively. Transmission electron microscopy (TEM) was employed to provide more detailed insight into the extrusion microstructure. TEM images of the conventionally and the subsequently hydrostatically extruded GW123 rods at peak aged condition (225 °C/21 h and 225 °C/9 h) are presented in Fig. 1c and d. As can be seen, a large amount of fine plate-shaped precipitates was observed in both extruded alloys. The continuity and size of precipitates varied between the two extrusion microstructures and lied between 20 nm and 80 nm in length. Selected area diffraction (SAD) patterns were taken with the incident beam parallel to $[0001]_\alpha$ to identify the second phase precipitates. As revealed in Fig. 1c and d, the peak-aged microstructure predominantly consists of metastable β′ phase found in Mg–Gd alloys. Compared to the conventionally extruded alloy with continuous precipitation, hydrostatic extrusion after conventional extrusion gave rise to a discontinuous precipitate structure with a much finer precipitate size. In terms of extruded surface quality and formability, hydrostatic extrusion at room temperature following hot conventional extrusion showed no signs of cracks (Fig. 2).

Fig. 2. Top view of hydrostatically extruded bars at room temperature after hot conventional extrusion.

3.2. Mechanical properties

The tensile mechanical properties of the GW123 alloy at room temperature including hardness (HV), ultimate tensile strength (UTS), tensile yield strength (TYS) and maximum elongation (ε) are listed in Table 1. In comparison to the as-cast samples, the strength properties of the as-extruded samples increased significantly. Evidently, TYS, UTS and hardness have increased even more after a second extrusion trial by means of cold hydrostatic extrusion. In addition, heat treatments seem to improve the strength and hardness of the extruded material, which can be associated with the metastable β′ phase.

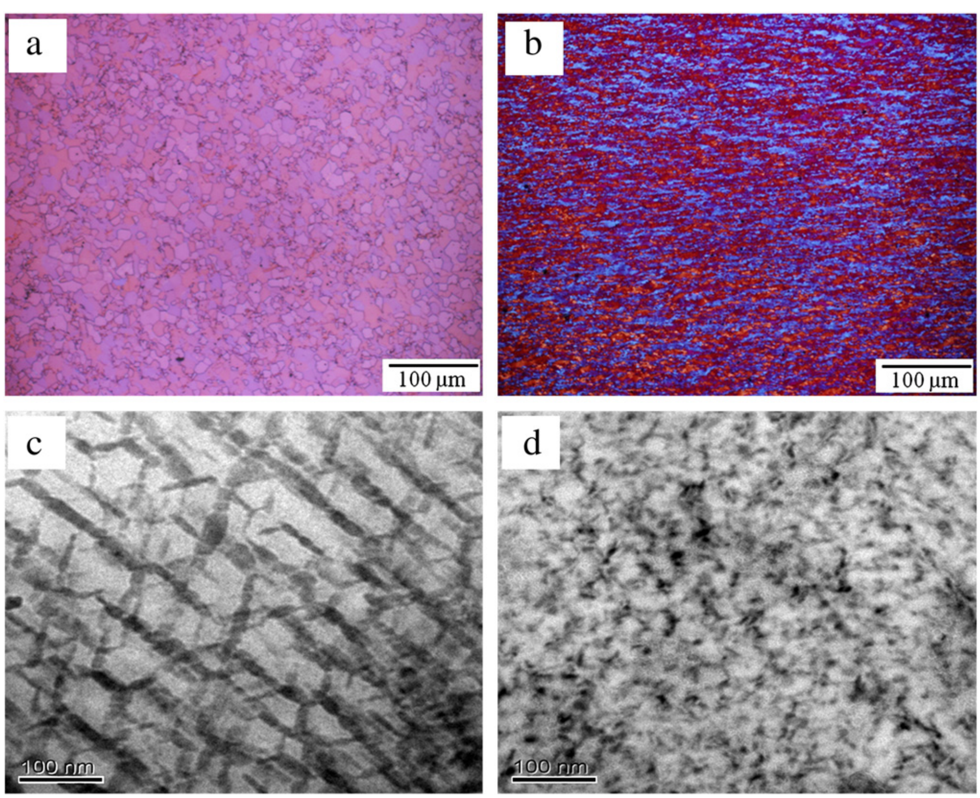

Fig. 1. Optical microstructure of the extruded GW123 alloy: (a) upon conventional extrusion at 430 °C; (b) upon subsequent hydrostatic extrusion at room temperature. The extrusion direction is horizontal. Bright field TEM images of the extruded GW123 alloy after peak aging: (c) conventionally extruded and aged at 225 °C/21 h and (d) after hydrostatic extrusion and aging at 225 °C/9 h.

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