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Excellent mechanical properties of an ultrafine-grained quasicrystalline strengthened magnesium alloy with multi-modal microstructure

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ABSTRACT

In this study, we have developed an excellent mechanical properties of an ultrafine-grained quasicrystalline strengthened magnesium alloys by conventional extruding as-casted Mg–1.5Zn–0.25Gd (at%) ingot at 373 K with an extrusion ratio of about 9:1. After extrusion, multi-modal microstructure was formed, i.e. exhibited large deformed grains surrounded by fine dynamical recrystallization grains and the mean grain sizes smaller than 1 μm. The extruded sample shows excellent tensile properties at ambient temperature with ultimate tensile strength of 417 MPa, 0.2% proof stress of 395 MPa and elongation to failure of 8.3%. The notable improvement in strength mainly attributed to the grain refinement, dense distribution of the fine precipitates inside the fine dynamical recrystallization grains and the high intensity of typical basal texture.

1. Introduction

As light-weight structural materials, wrought magnesium alloys hold substantial promise for a wide range of applications especially in automotive and 3C industry [1]. However, they suffer from a couple of drawbacks, such as inferior formability at room temperature and lower 0.2% proof strength [2], poor heat resistance [3]. To overcome these disadvantages, zinc is currently used as an alternative alloying ingredient because it helps prevent the Mg alloys from harmful corrosion [4]. Recently, it has been found that further addition of a small amount of rare-earth elements, e.g. Gd, can enhance the yield strength and elongation at ambient temperature significantly due to the formation of a thermally stable icosahedral quasicrystalline phase (I-phase) [5]. The effect of Zn/Gd ratio on the phase constituents of Mg alloys has also been investigated, leading to an interesting finding that the I-phase is the only secondary phase formed in the Mg alloys when the atomic ratio of Zn to Gd reaches 6 [6].

One of the another effective ways to enhance strength and ductility of Mg alloys is to achieve the multi-modal microstructure composed of coarse and fine grains [7,8], the impact of which on the improvement of mechanical properties of Mg alloys is twofold. On one hand, the coarse-grain region with a strong basal texture strengthening the tensile strength. On the other hand, the dynamically recrystallized a-Mg fine-grain region with random orientation enhances strength and ductility of Mg alloys. For instance, the Mg–2.2Sn–0.5Zn–1.0Al (at%) [9] and Mg–3.5Al–3.3Ca–0.4Mn (wt%) alloys [10] reported with high strength. To obtain the multi-modal microstructure, it is often necessary to process the alloys at low temperatures or low extrusion ratios in order to suppress dynamic recrystallization and activate deformation twinning. In this work, we show a successful extruded the as-casted Mg–Zn–Gd alloys at a very low temperature of 373 K with an extrusion ratio of 9:1, aimed at achieving multi-modal microstructure and achieving high strength Mg alloy samples, and then shedding light on correlation between microstructures and mechanical properties of the quasicrystalline strengthened Mg.

2. Experimental procedure

The Mg–1.5Zn–0.25Gd (at%) alloys were prepared by first melting Mg and Zn metals of high purity (99.9%) as well as Mg–90Gd master alloy (wt%) under a mixed gas atmosphere of SF_6 (1 vol%) and CO_2 (99 vol%). The alloy liquids poured into a steel mold, which has a cylindrical cavity with a dimension of 40 mm in diameter and of 120 mm in height and is preheated at 373 K. The billets were cut from the ingot with a dimension of 37 mm in diameter and of 5 mm in height. The sliced billets were preheated at 373 K for 1 h in an

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extrusion mold, followed by extrusion processing at 373 K with an extrusion ratio of about 9:1. The as-extruded alloy bars were eventually cooled down through water quenching. Microstructures were analyzed by optical microscopy (OM), scanning electron microscopy (SEM, Hitachi S4800), and transmission electron microscopy (TEM, JEOL JEM-2010F). Specimens for OM and SEM observations were prepared by etching the extruded bars in a solution containing 1 g oxalic, 1 mL nitric acid, 1 mL acetic acid, and 150 mL distilled water. The TEM samples were prepared using the standard mechanical polishing and ion-beam thinning process. Specimens for tensile and compressive tests were prepared by cutting extruded bars along the extrusion direction (ED), and tests were carried out under a strain rate of $1 \times 10^{-3}\ s^{-1}$ at room temperature using the Zwick/Roell Z020 testing machine controlled by a computer. At least three different specimens had been tested for the samples treated at each condition to avoid measurement error. The yield strength was assumed as 0.2% proof stress. Texture analysis of the as-extruded bar was performed on their section perpendicular to the extrusion direction using X-ray diffractometer (XRD, PW3040/60).

3. Results

Fig. 1 shows OM and SEM micrographs of the extruded samples, from which there indeed appears a bimodal microstructure composed of dynamically recrystallized grains with a size of ~0.5 μm (DRXed region: fine equiaxed grains) and the elongated deformed grains (unDRXed region: white strips in Fig. 1(a) and indicated by yellow arrows in Fig. 1(b)). The mean grain size of the sample is smaller than 1 μm, confirming that grains can be refined remarkably by lowering extrusion temperature to 373 K. At the same time, the elongated deformed grains region in Fig.1(b) seems to have grain boundary but the contrast is very weak, maybe this is sub-grain boundary. Fig. 1(c) is

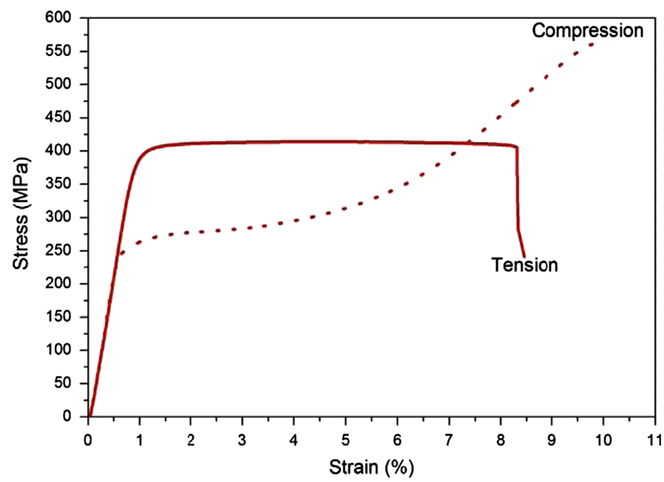

Fig. 3. Representative tensile and compressive stress–strain curves of the extruded samples.

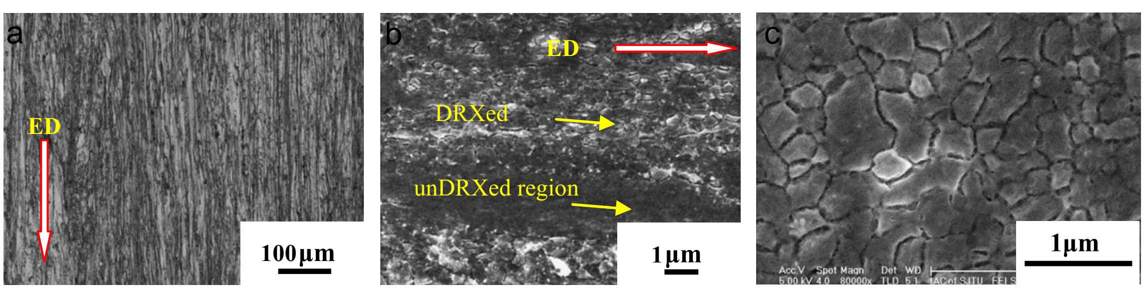

Fig. 1. (a) OM and (b) SEM microstructures images of the as-extruded samples. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

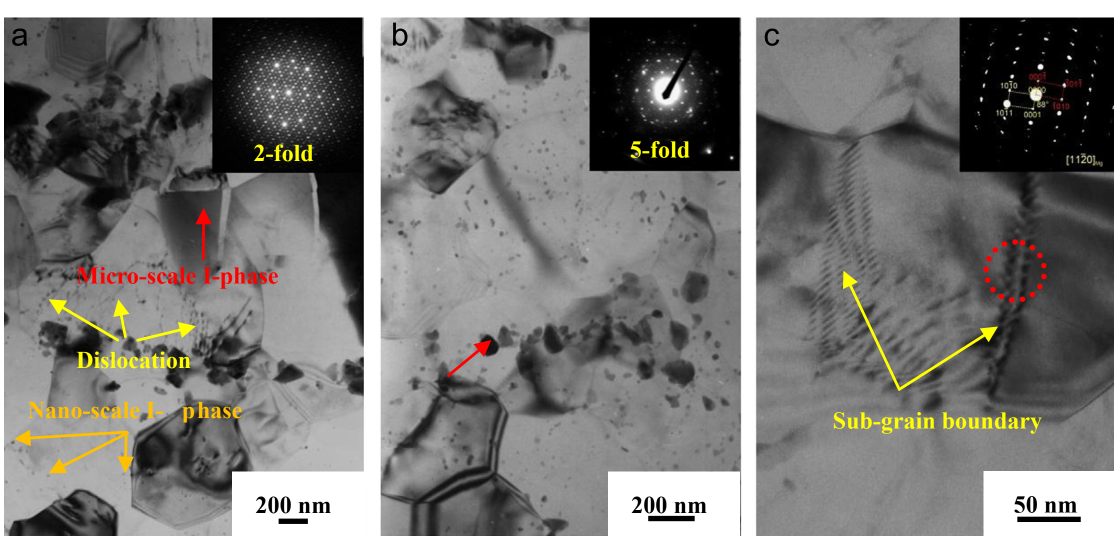

Fig. 2. TEM analysis results of the as-extruded samples. (a) Low magnified TEM image of sample, the inset in (a) is the SAED pattern of the particle label by red arrow; (b) high magnified TEM image show the precipitates in the sample, the inset in (b) is the SAED pattern of the particle label by red arrow; (c) high magnified TEM image show the low-angle grain boundary in the sample, the inset in (c) is the SAED pattern of the region outlined by the dashed circle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)