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JMST-1112; No. of Pages 7
ARTICLE IN PRESS
Journal of Materials Science & Technology xxx (2017) xxx–xxx
Contents lists available at ScienceDirect
Journal of Materials Science & Technology
journal homepage: www.jmst.org

Influence of size and distribution of W phase on strength and ductility of high strength Mg-5.1Zn-3.2Y-0.4Zr-0.4Ca alloy processed by indirect extrusion

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ARTICLE INFO

Article history:
Received 5 August 2017
Received in revised form 18 August 2017
Accepted 3 November 2017
Available online xxx

Keywords:
Mg alloy
Extrusion temperature
Mechanical properties
W phase
Dynamic precipitation
Bimodal structure

ABSTRACT

A high strength Mg-5.1Zn-3.2Y-0.4Zr-0.4Ca (wt%) alloy containing W phase ($Mg_3Y_2Zn_3$) prepared by permanent mold direct-chill casting is indirectly extruded at 350 °C and 400 °C, respectively. The extruded alloys show bimodal grain structure consisting of fine dynamic recrystallized (DRXed) grains and unrecrystallized coarse regions containing fine W phase and β_2' precipitates. The fragmented W phase particles induced by extrusion stimulate nucleation of DRXed grains, leading to the formation of fine DRXed grains, which are mainly distributed near the W particle bands along the extrusion direction. The alloy extruded at 350 °C exhibits yield strength of 373 MPa, ultimate tensile strength of 403 MPa and elongation to failure of 5.1%. While the alloy extruded at 400 °C shows lower yield strength of 332 MPa, ultimate tensile strength of 352 MPa and higher elongation to failure of 12%. The mechanical properties of the as-extruded alloys vary with the distribution and size of W phase. A higher fraction of DRXed grains is obtained due to the homogeneous distribution of micron-scale broken W phase particles in the alloy extruded at 400 °C, which can lead to higher ductility. In addition, the nano-scale dynamic W phase precipitates distributed in the unDRXed regions are refined at lower extrusion temperature. The smaller size of nano-scale W phase precipitates leads to a higher fraction of unDRXed regions which contributes to higher strength of the alloy extruded at 350 °C.

1. Introduction

Mg alloys have attracted much attention as light weight materials for vehicle and aerospace applications due to the increasing demand for reducing carbon dioxide emissions in transportation applications [1–4]. Wrought Mg-Zn-Y alloy is one of the main high strength Mg alloy systems [5–10]. Microstructures and mechanical properties of Mg-Zn-Y alloys mainly depend on the ratio of Zn/Y [11,12]. When the Zn/Y weight ratio varies between 2 and 7, the icosahedral quasicrystal phase (I-phase) will be formed in Mg-Zn-Y alloys [13–15]. The high crystal lattice symmetry of I phase and low interfacial energy between I phase and α-Mg matrix lead to a strong I phase/α-Mg interfacial bonding [16,17]. Xu et al. [18] report that an as-extruded Mg-5.5Zn-1.1Y-0.8Zr (wt%) alloy containing I phase exhibits an ultimate tensile strength (UTS, σ_b) of 345 MPa, 0.2% proof yield strength ($\sigma_{0.2}$) of 200 MPa and elongation to failure of 10.8%. The I phase particles are dispersed in α-Mg matrix and grain sizes are refined to 6–8 μm, which contribute to the excellent mechanical properties of the as-extruded Mg-5.5Zn-1.1Y-0.8Zr alloy [18]. When Zn/Y weight ratio is less than 1, long period stacking ordered (LPSO) phase will be formed in Mg-Zn-Y alloys [11,19–22]. The ultrahigh strength Mg-2.5Zn-6.8Y (wt%) alloy developed by rapidly solidified powder metallurgy (RS P/M) exhibits tensile yield strength (TYS) of 600 MPa and elongation to failure of 5% [23]. The ultrafine grain size of 200 nm and LPSO phase contribute to the ultrahigh strength of the RS P/M alloy. However, the complicated RS P/M process leads to the high cost of Mg-2.5Zn-6.8Y alloy, restricting their commercial applications "Your article is registered as a regular item and is being processed for inclusion in a regular issue of the journal. If this is NOT correct and your article belongs to a Special Issue/Collection please contact m.krishnan@elsevier.com immediately prior to returning your corrections."

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https://doi.org/10.1016/j.jmst.2017.11.022

Please cite this article in press as: H. Jiang, et al., J. Mater. Sci. Technol. (2017), https://doi.org/10.1016/j.jmst.2017.11.022

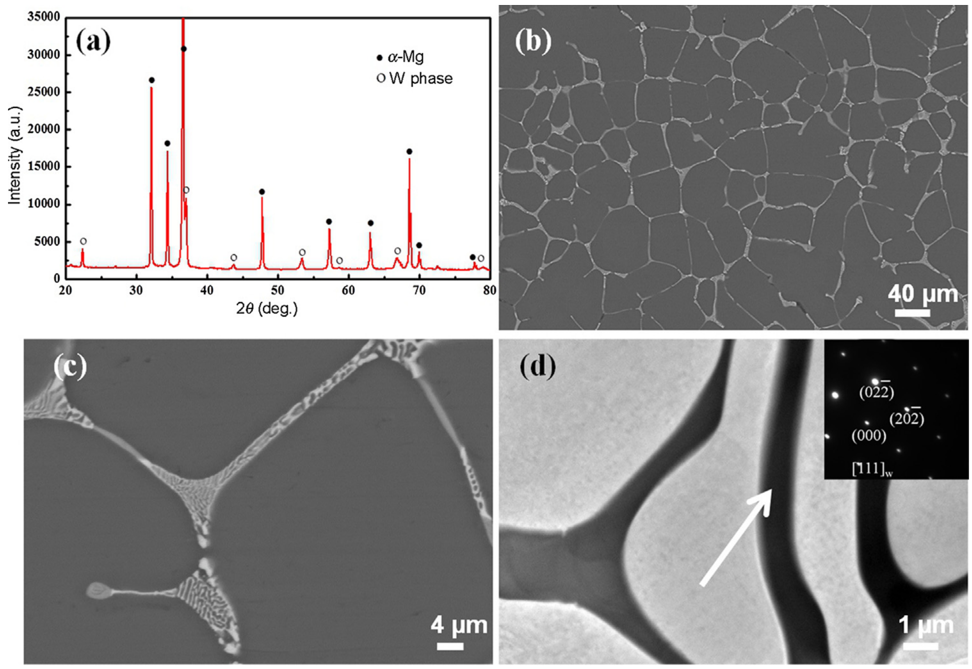

Fig. 1. XRD pattern (a), SEM images at low (b) and high (c) magnification of as-cast Mg-5.1Zn-3.2Y-0.4Zr-0.4Ca alloy and (d) TEM image of lamellar eutectic structure inserted with SAED pattern taken from area indicated by the arrow.

When Zn/Y weight ratio is about 1.4–2.5, W phase ($Mg_3Y_2Zn_3$) will be the main intermetallic compound in Mg-Zn-Y alloys [16,24]. W phase is reported to deteriorate mechanical properties of Mg-Zn-Y alloys due to their weak interfacial bonding with α-Mg matrix [24–26]. It is reported [18] that coarse W phase is too hard to be deformed during tensile test, therefore, W phase can induce a high stress concentration at particle/matrix interface, which could trigger the formation of voids and further lead to the nucleation of cracking, so the W phase has no strengthening effect on the as-cast Mg-5.5Zn-3.1Y-0.8Zr alloy [18]. After extrusion, coarse W phase is broken into fine particles and distributed along the extrusion direction, which contributes to the high performance of the as-extruded Mg-7Zn-6Y-0.6Zr (wt%) alloy with UTS of 280 MPa, TYS of 210 MPa and elongation to failure of 12% [12]. This suggests that the homogeneously distributed fine broken W-phase particles induced by hot extrusion may act as an effective dispersive strengthening phase [8,32]. In addition to the broken W phase, fine W phase can also precipitate during ageing treatment. For instance, in cast Mg-2Zn-1Y-0.6Zr (wt%) alloy [27], granule-shape W phase precipitates after T6 treatment, leading to obvious ageing strengthening.

In our previous research, an ultrahigh strength as-extruded Mg-10Zn-6Y-0.5Zr-0.3Ca alloy was developed [34]. The ultrahigh strength of the alloy is mainly attributed to a high density of broken W phase and nano W dynamic precipitates. In order to further investigate the influence of size and distribution of W phase on mechanical properties of Mg-Zn-Y alloys, microstructure and mechanical properties of Mg-5.1Zn-3.2Y-0.4Zr-0.4Ca (wt%) alloy extruded at different temperatures were investigated to develop low cost and high strength Mg-Zn-Y alloy.

2. Experimental

Mg-5.1Zn-3.2Y-0.4Zr-0.4Ca alloy was produced from pure Mg, pure Zn, Mg-30Y and Mg-25Zr and Mg-25Ca master alloys (all in wt.%). Ca and Zr were added in order to refine microstructure of Mg-Zn-Y alloy [28–30]. The alloy was prepared by permanent mold direct-chill casting [31]. Alloy melt was kept at 720 °C for 20 min in a cylinder steel crucible. Then the melt-containing crucible was immerged into the cooling water at a speed of 40 mm min^{-1}, then the ingot with a diameter of 60 mm and length of 140 mm was prepared. The rod billet with a diameter of 43 mm and height of 35 mm was cut from the ingot, then indirect-extruded at 350 °C and 400 °C, respectively, under a ram speed of 0.1 mm s^{-1} and an extrusion ratio of 12. The billet was hold at extrusion temperature for 10 min prior to extrusion. The cylindrical extrusion rods with a diameter of 12 mm and length of 230 mm were produced.

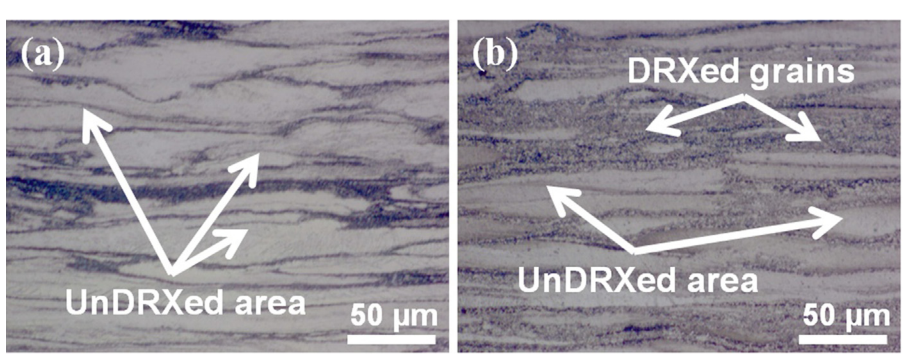

Fig. 2. OM micrographs of Mg-5.1Zn-3.2Y-0.4Zr-0.4Ca alloys extruded at 350 °C (a) and 400 °C (b).

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