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Effect of aluminum content on the texture and mechanical behavior of Mg–1 wt% Mn wrought magnesium alloys

M.Z. Bian [a,*], A. Tripathi [b], H. Yu [c], N.D. Nam [d], L.M. Yan [e,*]

[a] Department of Materials Science and Engineering, Monash University, Clayton Campus, Victoria 3800, Australia
[b] Department of Metallurgical Engineering & Materials Science, Indian Institute of Technology Bombay, Mumbai 400076, India
[c] School of Materials Science and Engineering, Hebei University of Technology, Tianjin 300132, China
[d] Petroleum Department, Petrovietnam University, Ba Ria City, Ba Ria-Vung Tau Province 74000, Viet Nam
[e] School of Materials Science and Engineering, Innermongolia University of Technology, Huhhot 010051, China

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ABSTRACT

The mechanical response of as-extruded magnesium–aluminum–manganese alloy with varying (1–4 wt%) aluminum content has been examined, while the concentration of manganese is kept constant at 1 wt%. Results indicated that microstructure exhibits more uniform and equiaxed grain structure, and gradual decrease of texture intensity with increasing aluminum content. Mechanical testing results revealed tensile and compressive yield strengths decreased, while yield anisotropy, tensile uniform elongation and strain hardening exponent increased with increasing aluminum content. Weaker texture was considered to be responsible for lower yield strength, and in particular for significant decrease in tensile yield strength. In addition, simulation results revealed that prismatic <*a*> and basal <*a*> slips played a very important role during tensile deformation, and the contribution of prismatic <*a*> slip decreased with increase in aluminum content. On the other hand, $\{10\bar{1}2\}$ twin was the major deformation mode at the initial stage of the compressive deformation in addition to the basal <*a*> slip, and the relative activity of the $\{10\bar{1}2\}$ twin decreased with increasing aluminum content.

1. Introduction

As the lightest structural material, magnesium and its alloys are regarded as promising candidates for lightweight applications in automobile, aerospace, light rail, high speed trains and 3C (computer, communication and consumer electronic) industries [1,2]. However, vast majority of their applications have been confined to casting alloys, and so far applications of wrought alloys have been very limited [3,4]. One of the technical problems that restrict immediate applications of wrought magnesium is its formability. It is well known that basal <*a*> slip and $\{10\bar{1}2\}$ twin are major deformation modes at ambient temperature for Mg and its alloys, because their critical resolved shear stress values are much lower than that of other deformation modes, such as prismatic <*a*>, pyramidal II $<c+a>$ slips and $\{10\bar{1}1\}$ twin [5–8]. As a consequence, a strong basal texture generally develops during plastic forming processes such as extrusion, rolling, and forging. Unfortunately, the strong basal texture delivers strong yield anisotropy and poor formability at ambient temperature due to limited number of active deformation modes [9,10]. To facilitate wider applications of wrought magnesium alloys as structural metals, it is desirable to weaken the texture intensity and thus improve the formability. Alloy addition provides a suitable way to achieve this goal in Mg alloys, as it is known as an effective method to weaken the harmful basal texture [11–15].

Aluminum is one of the most commonly used alloying elements and has the most favorable effect on Mg alloys. It is known that the addition of certain amount of Al can increase not only strength but also ductility [16]. For instance, AZ31 (Mg–3 wt% Al–1 wt% Zn–0.3 wt% Mn) is the most commonly available wrought magnesium alloy and many works have been done to investigate effect of Al content on the AZ series alloys [17–19]. Recently it has been reported that AM30 (Mg–3 wt% Al–0.4 wt% Mn) alloy shows better extrudability, ductility as well as formability than the commercial AZ31 alloy [20]. However, the effect of Al content on Mg–Al–Mn alloys has not yet been studied in a systematic manner. Furthermore, the change in deformation behavior, derived from the texture change due to Al addition, has not yet been critically examined. In the present study, Mg–*x*Al–1Mn rods with Al content (x) ranging from 1 to 4 wt% were

* Corresponding authors. Tel.: +61 3 990 50421.
E-mail addresses: minngzhebian@gmail.com (M.Z. Bian), yanliangming@126.com (L.M. Yan).

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extruded and their mechanical properties were characterized by tensile and compressive tests at room temperature. The initial and deformed textures after tensile and compressive tests were investigated using X-ray diffraction method to reveal the effect of Al content on the texture evolution.

2. Experimental procedure

Ingots were manufactured by an electrical resistance furnace under a mixed gas atmosphere of CO_2+0.5% SF_6. The cast ingots were homogenized at 400 °C for 12 h, and then immediately quenched in cold water. The ingots were then machined into cylindrical shaped rods for extrusion. Indirect extrusion was carried out at 300 °C with a ram speed of 0.4 mm/s and extrusion ratio of 23 to produce round bars. The alloy composition and corresponding designation are presented in Table 1. Tensile specimen with 4 mm in diameter and 16 mm in gauge length, and compressive specimens with 8 mm in diameter and 12 mm in height were machined from as extruded bars, with loading direction aligned along the extrusion direction, as shown in Fig. 1. Uni-axial tensile and compressive tests were performed at room temperature using a screw driven Instron™ testing machine at a strain rate of $1\times10^{-4}\ s^{-1}$.

Texture before and after tensile and compressive tests was measured by the Schulz reflection method using X-ray diffractometer with Cu Kα source. Corrections for peak defocusing and background intensity were made by experimentally determined defocusing curves established using powder samples having random texture. Microstructure of AM series alloy was observed using a FEG-SEM equipped with the TSL electron backscatter diffraction (EBSD) system operating at 20 kV at 70° tilt angle. An automated EBSD scan was obtained in the stage-control mode using TSL data acquisition software at a step size of 0.2 µm, and data having confidence index greater than 0.1 was used for analysis. The average grain size was calculated using a linear intercept method.

Crystal plasticity simulations were carried out using a visco-plastic self-consistent (VPSC) model [21–23]. The major slip and twinning modes, i.e. basal <a> slip, prismatic <a> slip, second order pyramidal II <c + a> slip and $\{10\bar{1}2\}$ tensile twinning have been included to simulate both tensile and compressive curves. This combination of deformation modes provided promising results with respect to the stress–strain curves as well as the texture evolution. The Voce-type hardening rule is used to describe the evolution of the threshold stress as a function of accumulated shear strain in the grain.

$$\tau_c^s = \tau_0^s + \left(\tau_1^s + \theta_1^s \Gamma\right)\left[1 - \exp\left(-\theta_0^s \Gamma / \tau_1^s\right)\right] \quad (1)$$

where Γ is the accumulated shear in the grain, τ_0^s, θ_0^s, θ_1^s and τ_1^s are initial critical resolved shear stress (CRSS), initial hardening rate, asymptotic hardening rate and back extrapolated stress respectively. In order to fulfill the twin reorientation problem during plastic deformation, predominant twin reorientation (PTR) scheme was implemented in the VPSC model. At each incremental step, the accumulated twin fraction in the individual twinning systems of each grain is compared with the threshold fraction $V^{th,mode}$ is defined as follows:

$$V^{th,\,mode} = A^{th1} + A^{th2}\frac{V^{eff,\,mode}}{V^{acc,\,mode}} \quad (2)$$

where $V^{acc,mode}$ and $V^{eff,mode}$ are accumulated twin fraction and effective twinned fraction respectively. The threshold values A^{th1} and A^{th2}, determine the evolution of twin volume fraction during plastic deformation. The parameters of the PTR-model are set as $A^{th1} = 0.8$ and $A^{th2} = 2.0$ for the $\{10\bar{1}2\}$ tensile twin. It is generally accepted that slip is rate sensitive, while twinning is usually considered to be rate insensitive [23]. Since the derivation of twin stress and an evolution of twinning during plastic deformation are the main focus of this study, a rate insensitive model has been adopted.

Table 1
Chemical composition (in wt%) of extruded AM series alloys.

Alloy	Al	Mn	Mg
AM11	0.93	0.86	Bal.
AM21	2.23	0.89	Bal.
AM31	3.09	0.90	Bal.
AM41	4.03	0.81	Bal.

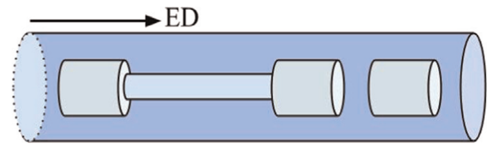

Fig. 1. Machining scheme of tension and compression specimens along the extrusion direction.

3. Results

3.1. Mechanical properties

True tensile and compressive stress–strain curves of as-extruded AM series alloys, loaded along the extrusion direction, are shown in Fig. 2(a). A solid line indicates tensile stress–strain curve and a dashed line represents compressive stress–strain curve. The tensile curve of AM11 alloy exhibits highest tensile yield stress (TYS) of 216 MPa, and lowest ultimate tensile stress (UTS) of 270 MPa among all the tensile curves. On the other hand, AM11 alloy shows the highest compressive yield stress (CYS) of 186 MPa and the highest ultimate compressive stress (UCS) of 429 MPa. Generally, strength increases with solute addition to Mg matrix, due to solid solution hardening, but in the present study, the strength decreased with increase in Al content, which will be discussed later in detail. While the tensile curves exhibit concave down appearance similar to those found in slip dominated deformation behavior, the compressive curves show concave up shape which is a typical feature of $\{10\bar{1}2\}$ twin dominated deformation behavior [24,25]. Thus, specimens tested in tension exhibit relatively higher yield stresses than specimens tested in compression. The yield anisotropy (CYS/TYS) is getting closer to 1 with increasing Al content, indicating better isotropic nature of AM41 alloy in comparison with AM11 alloy. Uniform tensile elongation (UTE) and strain hardening exponent (SHE) increase steadily with increase in Al content, as shown in Fig. 2(b). It is generally accepted that metals with high UTE and SHE usually have better formability at room temperature. Luo et al. [20] reported that SHE of wrought AZ31 and AM30 alloys is 0.14 and 0.17, respectively. The developed AM41 alloy which exhibits higher SHE value of about 0.19 potentially has better formability than AZ31 and AM30 alloys. Details of all the mechanical properties are summarized in Table 2.

3.2. Microstructure

Fig. 3 illustrates inverse pole figure (IPF) maps of as-extruded rods taken from sections perpendicular to the extrusion direction