Materials Science & Engineering A 588 (2013) 250–259

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Effect of strain ratio on cyclic deformation behavior of a rare-earth containing extruded magnesium alloy

F.A. Mirza [a], D.L. Chen [a,*], D.J. Li [b], X.Q. Zeng [b,**]

[a] Department of Mechanical and Industrial Engineering, Ryerson University, 350 Victoria Street, Toronto, Ontario M5B 2K3, Canada
[b] The State Key Laboratory of Metal Matrix Composites, School of Materials Science and Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, PR China

ARTICLE INFO

Article history:
Received 18 July 2013
Received in revised form
22 August 2013
Accepted 7 September 2013
Available online 14 September 2013

Keywords:
Magnesium alloy
Low cycle fatigue
Strain ratio
Twinning
Texture
Tension–compression yield asymmetry

ABSTRACT

Cyclic deformation characteristics of an extruded Mg–10Gd–3Y–0.5Zr (GW103K) magnesium alloy were determined via the strain-controlled low cycle fatigue tests with varying strain ratios at a constant strain amplitude. Unlike the rare-earth (RE)-free extruded magnesium alloys, the present alloy exhibited symmetrical hysteresis loops in tension and compression in the fully reversed strain-control tests at a strain ratio of $R_\varepsilon = -1$. This was due to the presence of relatively weak crystallographic textures and the suppression of twinning–detwinning activities arising from the fine grain sizes and RE-rich particles. At a strain ratio of $R_\varepsilon = 0$ and 0.5, a large amount of plastic deformation occurred in the tensile phase of the first cycle of hysteresis loops due to the high positive mean strain values. With decreasing strain ratio, the hysteresis loops became wider. Fatigue life of this alloy was observed to be the longest in the fully reversed strain control at $R_\varepsilon = -1$, and it decreased as the strain ratio was deviated from $R_\varepsilon = -1$. A certain degree of mean stress relaxation was also observed in the non-fully reversed strain control (i.e., $R_\varepsilon \neq -1$ tests).

1. Introduction

Lightweighting in ground vehicles is nowadays deemed as one of the most effective strategies to improve fuel economy [1–3] and reduce anthropogenic environment-damaging emissions [2–6]. It has also been reported that the fuel efficiency of passenger vehicles can be enhanced by 6–8% for each 10% reduction in weight [7]. This has drawn a considerable interest in the application of lightweight metals and alloys in the transportation industry [8]. To manufacture lighterweight vehicles, several types of materials, such as, advanced high-strength steels, aluminum alloys, magnesium (Mg) alloys, and polymers, are being used in automotive and aerospace industries, but substantial reductions could be further achieved by employing Mg alloys [2,6–12]. The current major automotive Mg applications are mainly die cast parts including instrument panel beam, transfer case, transmission case, engine block, steering components, radiator support, and steering wheel [9–12]. As Mg alloys are expanding into more critical applications like powertrain, chassis and body areas, there is a great need for developing wrought Mg products with improved mechanical properties [12]. Despite the potential of substantial reductions in weight, most wrought Mg alloys exhibited a high degree of anisotropy and tension–compression yield asymmetry due to the presence of strong crystallographic texture owing to their hexagonal close-packed (HCP) structure and limited deformation modes during extrusion or rolling processes [13–20]. For the vehicle components subjected to dynamic or alternating cyclic loading, such mechanical anisotropy and tension–compression yield asymmetry could result in irreversibility of cyclic deformation which may exert an adverse influence on the material performance [15]. These problems could be conquered through texture modification via alloy composition adjustment i.e., addition of rare earth (RE) elements [15,21–27]. Ball and Prangnell [19] first observed a weaker and more random texture after extrusion in Mg alloys with RE elements content. Recently, tremendous attention has been paid to a number of rare-earth (RE) elements, such as Gd [21,22,28–40], Y [21,22,28–33,35,37,39–42], Ce [22,27, 37,41,43], La [34,37,41,43], and Nd [22,41,42,44–47] added in Mg alloys. It has also been established that RE elements such as Gd, Nd, Ce, and La are effective texture modifiers for Mg alloys and they are being able to produce the so-called "RE texture component" even at low alloying levels [21,22,25–27,37,38,43]. These studies suggested that the "RE texture component" is well oriented for basal slip when tested in the appropriate orientation, which results in a substantial gain of ductility and a reduction of the tension–compression asymmetry in the conventional wrought Mg alloys. Although the alteration in the tension–compression

* Corresponding author. Tel.: +1 416 979 5000x6487; fax: +1 416 979 5265.
** Corresponding author. Tel.: +86 21 5474 2911; fax: +86 21 3420 2794.
E-mail addresses: dchen@ryerson.ca (D.L. Chen), xqzeng@sjtu.edu.cn (X.Q. Zeng).

0921-5093/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.msea.2013.09.023

yield asymmetry due to the addition of RE elements is being increasingly enlightened, the potential advantage of such extruded RE-Mg alloys as load-bearing structural components under cyclic loading condition has not been well appreciated. The earlier studies were conducted mainly on the high cyclic fatigue properties of the RE-containing Mg alloys [15,48–52]. Studies on the strain-controlled low cycle fatigue behavior of RE-containing Mg alloys remain limited to date [29,40,53–55]. For example, Wang et al. [40] investigated the cyclic deformation and low cycle fatigue behavior of an extruded Mg–8.0Gd–3.0Y–0.5Zr (GW83) alloy under fully reversed strain-controlled tension–compression loading along the extrusion direction. Wu et al. [53] reported strain controlled low cycle fatigue tests for a Mg–10Gd–2.0Y–0.46Zr alloy at 573 K. Fu et al. [54] studied the low cycle fatigue behavior of AZ91D alloy with varying amounts of rare-earth element content (Ce) at room temperature, with triangular waveform, frequency of 1 Hz and strain amplitude from 0.2% to 1.2%. To the authors' knowledge, there is no systematic studies on the low cyclic fatigue behavior of RE-containing magnesium alloys with emphasis on the effect of strain ratio has been reported in the open literature. The questions remain elusive on what degree of tension–compression asymmetry and cyclic stress response would be present in the RE-Mg alloy due to the effect of strain ratio, and what are the effects of RE elements on the twinning–detwinning activities during cyclic deformation. The present study was, therefore, aimed at exploring cyclic deformation behavior of an extruded Mg–10Gd–3Y–0.5Zr (GW103K) alloy under constant strain amplitude with different strain ratios.

2. Material and experimental procedure

The alloy used in the present investigation was a recently developed extruded magnesium alloy with the following composition (wt%): 10Gd, 3Y, 0.5Zr, and Mg (balance). The received alloy bars with a diameter of 20 mm were extruded at 400 °C with an extrusion ratio of 9:1. Microstructural examinations were performed using an optical microscope (OM) equipped with Clemex quantitative image analysis software and scanning electron microscope (SEM) JSM-6380LV equipped with Oxford energy dispersive X-ray spectroscopy (EDS) system and 3D imaging capacity. Standard metallographic sample preparation techniques were used with an etchant based on an acetic picral solution containing 4.2 g picric acid, 10 ml acetic acid, 10 ml H_2O, and 70 ml ethanol. The average grain size was measured via a linear intercept method. The texture was determined by measuring incomplete pole figures between $\Psi = 0°$ and 75° in the back reflection mode using a PANalytical X-ray diffractometer with Cu K_α radiation at 45 kV and 40 mA and analyzed using MTEX software, and defocusing due to the rotation of sample holder was corrected using experimentally determined data obtained from the diffraction of magnesium powders received from Magnesium Electron. Sub-sized fatigue samples in accordance with ASTM E8 standard were machined with the loading axis parallel to the extrusion direction (ED). The samples had a gauge length of 25 mm (or a parallel length of 32 mm) and a width of 6 mm. The thickness of the samples was 6 mm as well. The gage section of fatigue samples was ground progressively along the loading direction with emery papers up to grit number of 600 to remove the machining marks and to achieve a consistent surface.

Strain-controlled, pull–push type fatigue tests were conducted using a computerized Instron 8801 fatigue testing system via Fast Track Low Cycle Fatigue (LCF) program at a constant strain rate of 1×10^{-2} s^{-1} and room temperature of 25 °C. To study the strain ratio effect on the low cycle fatigue behavior of GW103K alloy, five different strain ratios $R_\varepsilon = 0.5$, 0, -1, -3, and $-\infty$, were used at a given total strain amplitude of 0.8% and at least two samples were tested at each level of the strain ratio. Triangular loading waveform was applied during the tests. For the sake of comparison, some samples of extruded RE-free AM30 magnesium alloy (with a

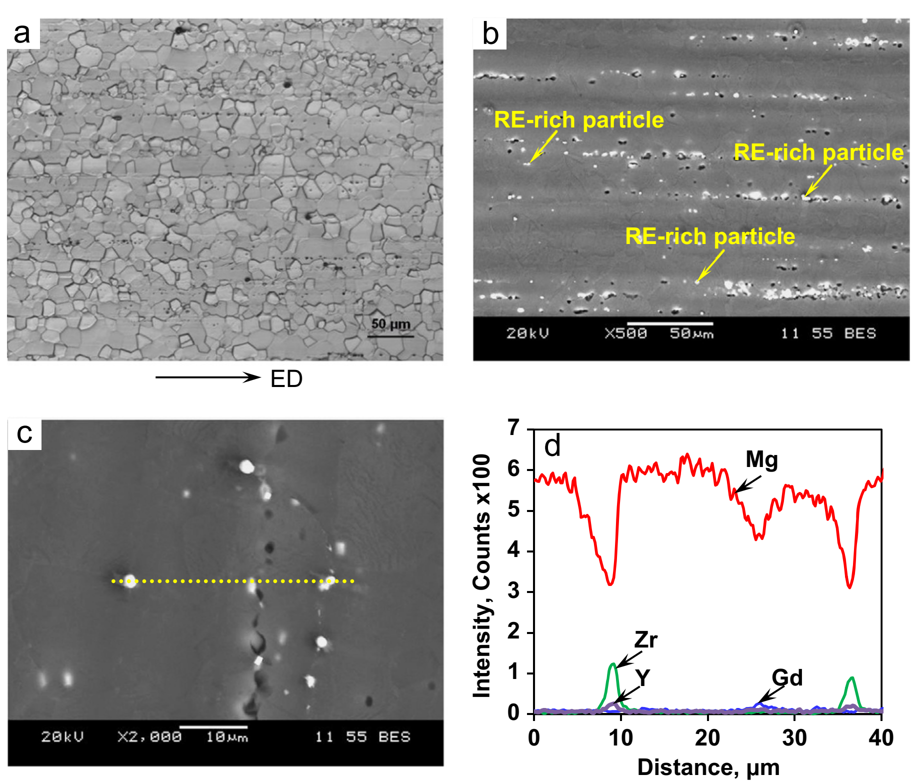

Fig. 1. Microstructure of the extruded GW103K alloy: (a) optical micrograph (where ED denotes the extrusion direction), (b) SEM back-scattered electron image at a lower magnification, (c) SEM back-scattered electron image at a higher magnification indicating EDS line scan position, and (d) the corresponding EDS line scan results.