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Strain-controlled low cycle fatigue properties of a rare-earth containing ME20 magnesium alloy

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ABSTRACT

The present study was aimed to evaluate the strain-controlled cyclic deformation characteristics and low cycle fatigue (LCF) life of a low (~0.3 wt%) Ce-containing ME20-H112 magnesium alloy. The alloy contained equiaxed grains with ellipsoidal particles containing Mg and Ce ($Mg_{12}Ce$), and exhibited a relatively weak basal texture. Unlike the high rare earth (RE)-containing magnesium alloy, the ME20M-H112 alloy exhibited asymmetrical hysteresis loops somewhat similar to the RE-free extruded Mg alloys due to the presence of twinning-detwinning activities during cyclic deformation. While cyclic stabilization was barely achieved even at the lower strain amplitudes, cyclic softening was the predominant characteristics at most strain amplitudes. The ME20M-H112 alloy showed basically an equivalent fatigue life to that of the RE-free extruded Mg alloys, which could be described by the Coffin-Manson law and Basquin's equation. Fatigue crack was observed to initiate from the near-surface imperfections, and in contrast to the typical fatigue striations, the present alloy showed some shallow dimples along with some fractions of quasi-cleavage features in the crack propagation area.

1. Introduction

Due to the increasing global energy demand and great cognizance of human-caused pollution such as CO_2 emissions in recent years, lightweighting has turned into a crucial approach in the automotive and aerospace industries [1–10]. There has been major interest and great deal of research activity for finding alternatives to reduce the fuel consumption of passenger vehicles [10,11]. Being the ultra-lightweight structural metallic material, magnesium (Mg) alloys have been increasingly applied in the auto industry for vehicles weight reduction [12]. The application of Mg alloys as a structural material in automotive and aerospace industry would require the evaluation of fatigue and cyclic deformation characteristics, since structural components would unavoidably experience dynamic loading in service, which leads to the occurrence of fatigue failure [13–15]. Thus, to guarantee the structural integrity and durability of such engineering components it is essential to understand the fatigue and cyclic deformation behavior of Mg alloys. As there is a growing application of Mg alloys in powertrain, chassis and body areas, developing wrought Mg components with improved mechanical properties became a prominent necessity [16].

There are currently intensive studies in the development of Mg alloys with high strength, good corrosion resistance and superior formability for structural applications [6,12,14,16–28]. Nevertheless, several restraints are faced in the application of Mg alloys, including limited ductility, tension-compression yield asymmetry, pronounced directional anisotropy arising from the presence of strong crystallographic texture related to their hexagonal close-packed (HCP) structure due to a limited number of slip systems that could activated during extrusion or rolling processes [29–31]. For the vehicle components subjected to dynamic cyclic loading, this mechanical anisotropy along with the tension-compression yield asymmetry could lead to irreversibility of cyclic deformation, which may have a serious influence on the material performance [32]. Both the tension-compression yield asymmetry and formability at room-temperature could be effectively improved by the addition of alloying elements, especially rare-earth (RE) elements due to their affinity to induce texture randomization during hot deformation processes (e.g., extrusion or rolling), which results in the decrease of texture intensities and the activation of basal slip [29,33–38]. Though these alterations in the tension-compression yield asymmetry and mechanical anisotropy due to RE elements additions are recently reported, the potential advantage of such wrought RE-Mg alloys as structural components under dynamic cyclic loading conditions has not yet been well appreciated.

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Recently several studies on the fatigue of RE-Mg alloys have been reported in the literature [29,39–47]. For instance, Yang et al. [29] conducted very high cycle fatigue tests of a high RE-containing extruded Mg-12Gd-3Y-0.5Zr alloy, and observed much relieved tension-compression yield asymmetry and enhanced fatigue failure resistance in comparison with RE-free AZ31 alloy. The fatigue strength of extruded Mg-10Gd-1Nd and Mg-10Gd alloys in the form of *S-N* curves was also evaluated via stress-controlled high cycle fatigue tests [47]. A few strain-controlled low cycle fatigue tests on the RE-Mg alloys have been performed as well [48–55]. Although the high performance of the Mg–10Gd-3Y-0.5Zr (GW103K) alloy was achieved [48–50], it was quite expensive due to the addition of a fairly high amount (totally ~13 wt%) of RE elements. Since the cost is one of the major considerations in the automotive applications, recently developed rolled ME20M-H112 alloy with a low amount of RE element (~0.3 wt% Ce) would be a promising candidate. To the authors' knowledge, no studies have been conducted on the cyclic deformation behavior of ME20M-H112 Mg alloy under strain control in the open literature. It is unclear to what extent the ME20M-H112 alloy would exhibit the tension-compression asymmetry, whether cyclic hardening or softening would occur, and what are the cyclic stress response and fatigue life. Therefore, the objective of the present study was aimed at identifying cyclic deformation behavior of a low RE-containing rolled ME20M-H112 alloy, and evaluating the fatigue life under varying strain amplitudes.

2. Material and experimental procedure

The material under investigation in the present study is a newly developed Mg alloy ME20 sheet, which was processed by hot rolling and H112 tempered, whose nominal composition is provided in Table 1. Microstructural evolution was examined in the samples by 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. Standard metallographic sample preparation techniques were used to grind and polish sample surfaces, and etching was done with an acetic picral solution containing 4.2-g picric acid, 10-ml acetic acid, 10-ml H_2O, and 70-ml ethanol. Textures were obtained using a PANalytical X-ray diffractometer (XRD) with Cu K_α radiation at 45 kV and 40 mA in a back reflection mode by measuring partial pole figures (i.e., ranging between $\Psi=0°$ and 75°). Texture data were afterwards analyzed based on MTEX software [56]. It should be noted that the defocusing stemming from the rotation of the XRD sample holder was corrected using the experimental data obtained from Mg powder diffraction. The sample was positioned in the machine with the rolling direction parallel to the *x*-direction and defocusing arising from the rotation of XRD sample holder was corrected using experimentally determined data obtained from the diffraction of Mg powders received from Magnesium Elektron. Sub-sized tensile and fatigue samples were machined with the loading axis parallel to the rolling direction (RD) in accordance with ASTM: E8 standard. The samples had a gauge length of 25 mm (or a parallel length of 32 mm), thickness of ~7 mm, and a width of ~6 mm. The gauge section of tensile and fatigue samples was ground progressively along the loading direction with emery papers up to a grit number of 600 to remove the machining marks and to achieve a smooth surface.

Tensile tests were performed in accordance with the ASTM: E8 standard by means of a computerized United tensile testing machine with a gauge length of 25 mm at a strain rate of $1\times10^{-3}\ s^{-1}$ at room temperature. Strain-controlled "pull-push" type fatigue tests (in accordance with the ASTM: E606 standard) were conducted in air at room temperature with a 25 mm extensometer using a computerized Instron 8801 fatigue testing system that was controlled by a Fast Track Low Cycle Fatigue (LCF) program. The cyclic deformation test conditions consisted of a zero mean strain (i.e., a strain ratio of $R_\varepsilon=-1$, completely reversed strain cycle) and a constant strain rate of $1\times10^{-2}\ s^{-1}$ with triangular loading waveform, as noted in the ASTM: E606 standard for continuous cyclic tests and generally for strain-rate sensitive materials, since the triangular waveform results in a constant strain rate in the course of cycling. Low cycle fatigue tests were performed at total strain amplitudes of 0.2%, 0.4%, 0.6%, 0.8%, 1.0%, and 1.2% (at least two samples were tested at each level of the strain amplitudes). At lower strain amplitudes (e.g., 0.1% and 0.2%), strain-controlled tests were sustained for 10,000 cycles before being converted to load control, with a sine cyclic waveform at a frequency of 50 Hz. Once tests were completed, SEM was used to examine the fracture surfaces of fatigued samples, aiming to identify the various features involving fatigue initiation and propagation mechanisms. In addition, a special interest was given to the near fracture surface areas of the fatigued samples, which were cut, mounted, ground, polished and etched to examine the eventual appearance of residual twins.

3. Results and discussion

3.1. Initial microstructure and texture

Fig. 1 shows a typical optical micrograph and a backscattered electron (SEM) image of a rolled ME20M-H112 alloy, where the arrow indicates the rolling direction (RD). The microstructure of the alloy was composed of equiaxed grains with an average grain size ~12 μm due to the dynamic recrystallization occurred in the rolling process [48]. The grain size was fairly small in comparison with the common extruded Mg alloys, such as AZ31 and AM30 [14,16–19]. This was due to the role of added RE elements [48–50] and the grains can be prohibited from coarsening during the hot deformation process as cerium (Ce) can form some dispersed and thermally stable particles [57]. It was reported that a uniform recrystallized grain structure was observed with a grain size decreasing from ~13 to ~10 μm as Ce content increased from 0% to 1% for rolled and rolled/annealed ME alloys [58,59]. A similar type of microstructure of as-cast ME alloys has been reported in refs. [60–62]. The microstructure of the ME20 sample also revealed a few dispersed, fine, ellipsoidal particles as seen from Fig. 1(b) (indicated using arrow). An EDS line scan was performed as shown in Fig. 2(a) and (b), which confirmed the presence of RE particle (Ce) along with Mn. The very fine solid particles were identified as pure Mn, where Li et al. [61] also reported the existence of similar ellipsoidal particles containing Mg and Ce ($Mg_{12}Ce$). Similar findings have been reported for ME20 alloys in Refs. [62–64].

Fig.3 shows the crystallographic textures (basal (0001), prismatic $(10\bar{1}0)$, and pyramidal $(10\bar{1}1)$ pole figures) of rolled

Table 1
Chemical composition of the rolled ME20M-H112 Mg alloy.

Element	Al	Zn	Mn	Ce	Si	Fe	Cu	Ni	Be	Mg
Content (wt%)	< 0.2	< 0.3	1.69–1.81	0.29–0.33	< 0.10	< 0.05	< 0.05	< 0.007	< 0.01	Balance