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Effect of strain rate on compressive mechanical properties of extruded Mg–8Li–1Al–1Ce alloy

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The compressive mechanical properties of Mg–8Li–1Al–1Ce alloy were investigated under quasi-static strain rates (0.0001/s, 0.001/s, 0.01/s, and 0.1/s) and high strain rates up to ~2700/s at room temperature. The experimental results indicate that the flow stress and strain rate sensitivity increase with increasing strain rate. Microstructure observation by optical microscopy reveals that the distribution of compound Al_2Ce is influenced by the strain rate: when strain rate is higher, the compounds Al_2Ce distribute in both α and β phases; when strain rate is lower, most of the compounds Al_2Ce distribute in β phase and in the boundaries between α and β phases. Furthermore, it is found that the twinning forms in extruded Mg–8Li–1Al-1Ce alloys when deformed at high strain rates, and the amount of twinning increases with increasing strain rate, the deformation mechanism of Mg–8Li–1Al–1Ce alloy at high strain rates is a combination of dislocation motion and twinning.

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1. Introduction

Magnesium–lithium (Mg–Li) alloys, as the lightest known metallic structural materials [1], have been applied in the fields of the aerospace, lightweight weapon, automobile, portable equipment, etc. [2–4]. However, the more extensive applications of these binary Mg–Li alloys are restricted due to their low strength, and some alloying elements are therefore added into binary Mg–Li alloys to improve their mechanical performance [5–11]. For example, aluminum element is often used as a solid solution strengthening element, and cerium element is one of the mostly used alloying elements to refine the grain size of magnesium alloys [12]. To thoroughly understand the deformation and fracture mechanisms for further improving the mechanical properties of Mg–Li alloys, the microstructures, mechanical properties, and the effect of alloying elements have been studied until now [8,13–15]. For instance, Drozd et al. [8] investigated the mechanical properties of ultra light Mg–Li–Al alloys LA43 and LA45 at elevated temperatures, their results demonstrated that the test temperature has a marked effect on the mechanical properties (yield strength and ultimate tensile strength) and deformation mechanisms. In our previous work, the microstructures and quasi-static mechanical properties of cast and extruded Mg–Li alloys were studied [13], the results show that the microstructure becomes refined and the mechanical properties enhanced after extruded. The effect of the addition of alloying elements Y [14], Sn [15] and Ca [16] on microstructures and mechanical properties of Mg–Li alloys were also analyzed, and the results of our previous work indicate that the grains of Mg–Li alloys were refined and the mechanical properties were improved due to the addition of alloying elements [14–16]. A critical content of alloying element corresponding to the maximum strength of Mg–Li alloy was determined experimentally in our work [15]. Under high strain rate conditions, Sha et al. [17] studied the dynamic deformation behavior of Mg–8Li alloy using Hopkinson pressure bar experimental techniques, it can be concluded from their results that, when the strain and strain rate reach critical values, the deformation localization (shear band) occurs, the damage mode of Mg–Li alloy under high strain rate is shear localization, while such a phenomenon is rarely found under quasi-static loading. The effect of Li amount on the crack propagation behavior and fracture mechanisms of Mg–Li alloys was also investigated under high strain rate [18]. It can be seen from the literatures that most studies were performed under quasi-static loading conditions, and the work associated with the high strain rate deformation and fracture mechanisms is quite limited. However, the structures and components made by these light-weight alloys are often subjected to dynamic loading during their manufacture and service, it is therefore essential to study the mechanical properties of Mg–Li alloys under high strain rate, as the mechanical response and failure mechanisms of Mg–Li alloys under high strain rate is dramatically different from that under quasi-static loading.

In this work, the compressive mechanical response and the strain rate sensitivity of Mg–8Li–1Al–1Ce alloy at various strain rates are studied under room temperature, and the deformation mechanisms of the Mg–Li alloy is also addressed based on microstructure observation.

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2. Material and experimental procedure

The material used in this work is an extruded Mg–8Li–1Al–1Ce alloy, the chemical composition is given in Table 1. Two main processes, casting and extrusion, were employed to obtain Mg–Li alloy for experimental investigation. Firstly, the pure magnesium, lithium, aluminum and Mg–26Ce master alloy were melted in a vacuum melting furnace with argon atmosphere and then put in a permanent mold to obtain an ingot with a diameter of 50 mm; secondly, the cast Mg–8Li–1Al–1Ce alloy was reheated to 573 K and kept this temperature for 12 h in a furnace with protective gas, and then it was squeezed into rod at the extruding speed of 2.0 m/min. The rod with a diameter of 14 mm was finally produced for microstructure observation and mechanical tests.

Specimens for microstructure observation were cut from the extruded rod and then mounted, polished, and etched using 1 vol.% nital, their microstructures were analyzed using an optical microscopy (LEICA DM IRM). The phase structure of the Mg–Li alloy was analyzed by X-ray diffraction (D/Max2500PC Rigaku) with monochromatic Cu Kα radiation, and 2-theta angle range of 15°–85°, XRD phase identification was assisted by MDI Jade software. Specimens for compression tests under quasi-static and high strain rates were regular cylinders with dimensions 5 mm diameter × 5 mm length, they were directly machined from the extruded rod using EDM. The mechanical tests were performed at room temperature, and the loading axis was parallel to the extruded direction of the Mg–Li alloy. Quasi-static compression tests were carried out on Instron 8800 load frame at the strain rates of ~0.0001/s, ~0.001/s, ~0.01/s and ~0.1/s in accordance with the ASTM E9-09. The high strain rate compression tests were carried out on a split Hopkinson pressure bar (Fig. 1), which mainly consists of pressure gun, striker bar (projectile), incident bar, transmitted bar and the data acquisition system. The incident and the transmission bars were each 800 mm in length, while the striker bar having a length of 290 mm was used in this work. Both the bars and the projectile were of a diameter of 14.5 mm and comprised of a high strength steel.

The dynamic compression test is conducted by shooting the striker bar from a gas-gun. The striker bar impacts the incident bar, thereby generating an incident compressive stress pulse, whose amplitude and the duration are well-defined by adjusting the velocity and the length of the striker bar. This loading pulse propagates along the incident bar toward the specimen. When the incident pulse reaches the interface between the incident bar and the compressive specimen, part of the incident pulse is transmitted through the specimen and into the transmission bar as a compressive pulse, deforming the compression specimen. Simultaneously, the remainder of the incident pulse is reflected back into the incident bar as a tensile stress pulse. The incident $\varepsilon_t\,(t)$ and the reflected $\varepsilon_r\,(t)$ strains are measured by strain gauges glued at the midpoint of the incident bar, while the transmitted $\varepsilon_t\,(t)$ strain is measured by the strain gauge glued at the midpoint of the transmission bar. It is worth noting that the incident and transmitted strains are both compressive strains and are considered positive values, whereas the reflected strain represents a tensile strain and is negative These recorded signals are input into a computer program to achieve the stress (strain rate)–strain curves of the tested materials. Under stress equilibrium conditions, the stress, strain, and strain rate can be calculated using the transmitted ε_t and reflected ε_r strains in terms of one-dimensional stress wave theory [19] as:

$$\sigma(t) = E\frac{A_0}{A}\varepsilon_t(t) \tag{1}$$

$$\varepsilon(t) = \frac{2C_0}{L_0}\int \varepsilon_r(t)dt \tag{2}$$

$$\dot{\varepsilon}(t) = \frac{2C_0}{L_0}\varepsilon_r(t)dt \tag{3}$$

where σ is the engineering stress (MPa), ε the engineering strain, ε_t (t) the transmitted strain, ε_r (t) the reflected strain, $\dot{\varepsilon}(t)$ the strain rate (1/s), E the young modulus of incident and reflected bars (GPa), A the cross sectional area of incident and reflected bars (m^2), A_0, l_0 the cross sectional area and length of specimen (respectively m^2 and m), C_0 is the longitudinal wave velocity in the bars (m/s).

Table 1
Chemical composition of Mg–8Li–1Al–1Ce.

Element	Li	Al	Ce	Mg
wt.%	7.842	0.982	0.902	Balance

3. Results and analysis

3.1. Microstructure of the extruded Mg–8Li–1Al–1Ce alloy

The microstructures by an optical microscopy and XRD patterns of Mg–8Li–1Al–1Ce alloy are shown in Figs. 2 and 3, respectively. It can be seen from Figs. 2 and 3 that three phases, α phase (white), β phase (gray) matrix and compound Al_2Ce are found in Mg–8Li–1Al–1Ce alloy. Both α and β phases are elongated along the extruded direction, most of the compounds Al_2Ce distribute in β phases and in the boundaries between α and β phases.

3.2. Stress–strain response of the extruded Mg–8Li–1Al–1Ce alloy

Typical stress pulses ($\varepsilon_i(t)$, $\varepsilon_r(t)$, and $\varepsilon_t(t)$) recorded by strain gauges in Hopkinson pressure bar test are shown in Fig. 4. The typical shape of incident pulse is a square, while the shapes of reflected and transmitted pulses are different from that of incident pulse, which is dependent upon the properties of tested materials [20].

The stress, strain and strain rate are determined using these recorded reflected and transmitted pulses. However, it should be recognized that these mechanical parameters given by Eqs. (1) and (2) are the engineering stress and engineering strain. In order to calculate strain rate sensitivity, the true stress S and true strain δ need to be converted from engineering stress and strain using the following equation [21]:

$$\begin{cases} S = \sigma(1+\varepsilon) \\ \delta = \ln(1+\varepsilon) \end{cases} \tag{4}$$

Typical true stress–strain curves determined at various strain rates are potted in Fig. 5. It is noted that the flow stress increases gradually with increasing strain, and the flow stress also increases with increasing strain rate. The experimental facts that the flow stress increases with both increasing strain and strain rate indicate that the Mg–8Li–1Al–1Ce alloy has a strong work hardening behavior, the flow stress is quite sensitive to strain rate, which can be seen from the comparison among the flow stresses measured the same strain but different high strain rate. For example, at the same strain of ~0.12, the flow stress at strain rate of ~0.001/s is ~218 MPa, while at strain rate of ~1700/s it increases to ~ 292 MPa (see Fig. 5 for details), thereby the increment of the flow stress is calculated to be ~74 MPa when the strain rate increases to ~1700/s from 0.001/s, it is evident that the flow stress of Mg–8Li–1Al–1Ce alloy is strongly dependent of strain rate, Such a strain rate sensitivity can be also found in another magnesium-

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