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Effect of microstructure on tensile and compressive behavior of WE43 alloy in as cast and heat treated conditions

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ABSTRACT

The influence of heat treatment on the microstructure, tensile and compressive properties and failure mechanisms of WE43 alloy is studied. The eutectic phase is dissolved into the α-Mg phase and the grain size is refined in the heat treated alloy. Heat treatment improves the tensile yield and ultimate strengths by 40% and 53%, respectively. The compressive yield and ultimate strengths of heat treated alloy are also 55% and 23%, respectively, higher compared to the as-cast alloy. Compressive characterization is also conducted at high strain rates. The energy absorption capability of WE43-T5 specimens is higher than the as-cast WE43 specimens at all strain rates investigated in this work. Failure initiates with cracks in the eutectic phase in the as-cast alloy. These cracks grow through the grain to result in transgranular fracture. The absence of eutectic mixture in heat treated alloy results in grain boundary sliding and crack initiation at triple junctions. The crack propagation is delayed in the absence of eutectic precipitates, which improves the mechanical properties of the heat treated alloy.

1. Introductions

Magnesium alloys are the next generation light weight structural materials for aircraft, automobiles and biomedical implants. Low density, high specific strength and excellent machinability displayed by the new Mg-alloys are useful in these applications [1–6]. AZ series Mg-alloys containing aluminum and zinc have been studied extensively for mechanical properties and heat treatments [7,8]. Alloys containing rare earth (RE) alloying elements such as WE43 (Mg-4 wt% Y-3.3 wt% RE-0.5 wt% Zr) have been of interest recently as they have been certified as non-flammable. High-performance creep-resistant WE43 alloy shows useful high temperature properties, such as retention of strength at temperatures up to 300 °C and stability under long-term exposure up to 250 °C. In addition, WE43 has good corrosion and ignition resistance [9,10]. Additionally, heat treatment can further enhance the characteristics of this alloy [11–13]. These characteristics are being studied for biomedical implant applications to develop either permanent or resorbable implants [14,15]. Recent animal studies have shown that the as cast and heat treated WE43 magnesium alloys can be used for medical implant applications without imparting any toxicity [16].

Effects of RE elements on the microstructure and properties of Mg-alloys have been studied, which include the solid solution and precipitation hardening mechanisms and their effect on mechanical properties of this alloy [17]. It is reported that yttrium can provide solid solution strengthening, which is ascribed to the classical size and/or modulus misfit model and the valence effect in Mg matrix [18]. Neodymium can improve the creep resistance due to the combination of precipitation and solid solution hardening mechanisms [19]. Among the developed Mg-RE alloys, the Mg-Nd-Y system is attractive because it can be used at elevated temperatures [20]. WE54 (Mg–5.1%Y–1.5–2% Nd–0.5%Zr–3.25%RE) and WE43 alloys of this family have been studied in the published literature. Previous studies have reported the presence and orientation of second phases, such as grain boundary eutectic, Mg-RE precipitates, nanoscale cuboids, and zirconium-rich particles in a number of cast and heat treated alloys [21–25]. The microstructure of the alloys was investigated for distribution of these phases and their effects on the mechanical behavior were studied.

Solid solution strengthening and precipitation hardening mechanisms are found to improve the mechanical properties of Mg-RE alloys. The precipitation of a fine dispersion of intermetallics leads to high temperature strengthening [26]. Yttrium-containing Mg-alloys exhibit higher creep resistance up to 300 °C as well as have better corrosion resistance at the working temperature in comparison with other Mg-alloys. Yttrium has high solubility in magnesium and these alloys can be

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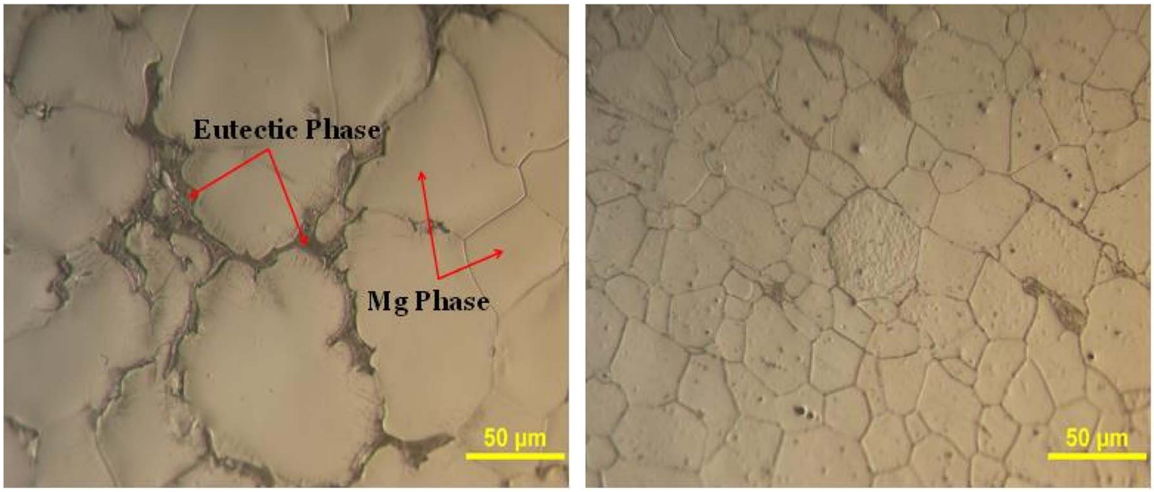

(a) (b)

Fig. 1. Optical micrographs of (a) as-cast and (b) T5 heat treated WE43 alloy specimens.

age hardened at low temperatures. Depending on the aging temperature, the precipitation sequence in Mg–Nd–Y alloys involves formation of β', β'' and β''' phases [26–30].

Plastic deformation prior to aging treatment has been applied to improve the dispersion of precipitates for Al alloys [31] and Mg alloys [32,33]. Moreover, studies on mechanical properties and creep behavior of as-cast [34–36] and heat treated [37–39] WE43 alloy reveal that hot-rolled WE43 shows hardness and strength substantially higher than those of the cast alloy. Also, a hot-rolled WE43 alloy with a T5 temper at 250 °C presented improved tensile properties than the one with a T6 temper at 250 °C because both strain hardening and artificial age hardening increase the strength of the alloy [40]. At high temperature of 375 °C, this alloy is found to display superplastic elongation behavior at very slow strain rates [41].

In the present work, a hot-rolling process was applied to WE43 alloy prior to T5 tempering. The microstructure evolution after the heat treatment was characterized and compared with cast alloy. Compression tests at various strain rates and tension tests were conducted to characterize the mechanical properties. The testing procedure is controlled in order to identify the failure mechanism under each loading condition.

2. Materials and methods

In order to heat treat, the as-cast alloy was scalped and hot rolled on a reversing mill down to 38-mm-thick plates at descending temperatures beginning in the range of 500 °C. These as-deformed (F-temper) plates were artificially aged at 210 °C for 48 h to obtain the peak aged (T5-temper) condition. The nominal composition of both samples was Mg-Y-RE-Zr (4 wt% Y, 3.3 wt% RE, 0.5 wt% Zr), where RE represents rare earth elements. For compression test, discs of 5 mm diameter were used. Dog bone specimens of 25 mm gauge length were machined for tension test as per ASTM E8 miniature test specifications. At least five specimens of each material are tested.

Standard metallography procedure was applied to polish the specimen surface before optical microscopy, which included sequential polishing down to 1 μm diamond slurry and etching with Nital etchant containing 5% nitric acid. An optical microscope (Nikon Epiphot 200) fitted with a Nikon DS-Fil digital camera and a scanning electron microscope (Hitachi S-3400N) equipped with an Energy dispersive Spectroscope (EDS) were used for the microstructure analysis. EDS analysis was performed at an acceleration voltage of 15 keV.

Quasi-static compression and tension tests were conducted on Instron 4469 universal test system equipped with a ± 50 kN load cell. An extensometer was used to obtain the strain data in tension testing. Load and cross-head displacement data were obtained from the testing and used for developing stress-strain graphs. A constant cross-head displacement rate of 0.2 mm/min was maintained, which corresponded to the nominal initial strain rate of 0.001 s^{-1}. The extensometer was used in tension test to collect strain data. At least five specimens for each material, cast WE43 and WE43-T5, were tested.

A split-Hopkinson pressure bar (SHPB) setup was used for the high strain rate (HSR) compression testing. The specimen was sandwiched between the incident and transmitter bars of 12.7 mm diameter and 1800 mm length. These Inconel alloy bars have Young's modulus and density of 195 GPa and 8190 kg/m^3, respectively. The strain pulses were recorded from the incident and the transmitter bars using strain gauges. The time dependent strain rate $\dot{\varepsilon}(t)$, stress $\sigma(t)$, and strain $\varepsilon(t)$ are calculated by

$$\dot{\varepsilon}(t) = \frac{2c_b\varepsilon_r(t)}{l_0} \quad (1)$$

$$\sigma(t) = \frac{AE\varepsilon_t(t)}{A_0} \quad (2)$$

$$\varepsilon(t) = \int_0^t \dot{\varepsilon}(\tau)d\tau \quad (3)$$

where c_b is the sound wave velocity in the bars; $\varepsilon_r(t)$ is the reflected strain recorded from the incident bar; $\varepsilon_t(t)$ is the transmitted strain recorded from the transmitter bar; A and E are the cross-sectional area and the elastic modulus of the bars, respectively; τ is the time variable used for integration; and A_0 and l_0 are the cross-sectional area and the length of the specimen, respectively. Nine specimens for as-cast WE43 and WE43-T5 each were tested.

3. Results and discussion

3.1. Microstructure analysis

The microstructure of as-cast WE43 alloy consists of bulk α-Mg phase with eutectic mixture present along grain boundaries, as observed in Fig. 1(a). The intermetallic phase present in the eutectic mixture is found to be $Mg_{24}RE_5$ [42]. During heat treatment, the eutectic phase is dissolved in α-Mg as observed in Fig. 1(b). The grain size of the as-cast and T5 specimens was measured from the optical micrographs to be 54.1 ± 18.6 and 24.8 ± 12.5 μm, respectively. Closer observation of the microstructure presented in Fig. 2(a) shows a lamellar structure of the eutectic mixture. EDS analysis presented in