Materials Chemistry and Physics 148 (2014) 28–31

Contents lists available at ScienceDirect

Materials Chemistry and Physics

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

Mechanical properties and strengthening behavior of Mg–Zn–MM alloy

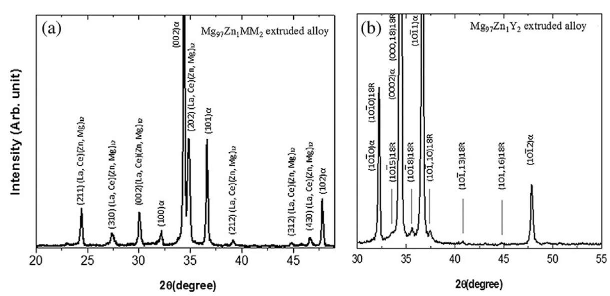
Jian-Yih Wang [a, *], Akhmad Saufan [a], P.H. Lin [a], H.Y. Bor [b], S. Lee [c], Y. Kawamura [d]

[a] Department of Materials Science and Engineering, National Dong-Hwa University, Hwa-Lian 97401, Taiwan
[b] Materials and Optoelectronics Research Division, Chung Shan Institute of Science and Technology, Taoyuan 32500, Taiwan
[c] Department of Mechanical Engineering, National Central University, Jhongli, Taiwan
[d] Department of Materials Science, Kumamoto University, Kumamoto 860-8555, Japan

HIGHLIGHTS

- The microhardness of second phase in $Mg_{97}Zn_1MM_2$ is higher than that of $Mg_{97}Zn_1Y_2$.
- The second phase in $Mg_{97}Zn_1MM_2$ is identified as $(La,Ce)(Mg,Zn)_{12}$ phase.
- The second phase in $Mg_{97}Zn_1MM_2$ can be refined remarkably by rolling.
- The strengthening mechanism of $Mg_{97}Zn_1MM_2$ is dispersion hardening.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 14 November 2013
Received in revised form
1 May 2014
Accepted 7 July 2014
Available online 31 July 2014

Keywords:
Alloys
Hot working
Mechanical testing
Electron microscopy
Mechanical properties
Microstructure

ABSTRACT

The mechanical properties of $Mg_{97}Zn_1MM_2$ alloy were studied. Owing to high hardness of its second phase, the yield strength of as-extruded $Mg_{97}Zn_1MM_2$ alloy exceeds that of $Mg_{97}Zn_1Y_2$ alloy. The microstructure is identified that the second phase in $Mg_{97}Zn_1MM_2$ alloy is $(La,Ce)(Mg,Zn)_{12}$. The hot rolling can refine the size of the second phases and disperse them uniformly. Hot rolling of $Mg_{97}Zn_1MM_2$ alloy at 773 K provided a yield strength of 300 MPa. The strengthening mechanism of $Mg_{97}Zn_1MM_2$ alloy is dispersion hardening by a strong second phase while that of $Mg_{97}Zn_1Y_2$ alloy is precipitation strengthening by a long-period stacking ordered phase.

1. Introduction

Increasing the strength of magnesium alloys is essential to expanding their range of applications in the automobile, railway and aerospace industries. The most important approach to improve mechanical properties of magnesium alloys is with additional alloying elements such as Zn, Ca, Y and rare earth (RE). Commercially available magnesium alloys are AZ- and AM-series [1], but higher strength of Mg–Y and Mg–RE alloys are attracting great attention and being much carried on [2–4]. Although commercial heat resistant ZE- and WE-series alloys have been used in industry, a lot of researches have been worked with Y or RE-containing magnesium alloys in order to improve the creep [5–7] and

* Corresponding author. Tel.: +886 3 8634230; fax: +886 863 4200.
E-mail addresses: jy-wang@yahoo.com.tw, jywang@mail.ndhu.edu.tw (J.-Y. Wang).

http://dx.doi.org/10.1016/j.matchemphys.2014.07.004
0254-0584/© 2014 Elsevier B.V. All rights reserved.

Table 1
Alloys compositions as analyzed by ICP-AES (wt.%).

Alloys	Y	La	Ce	Zn	Mg
$Mg_{97}Zn_1Y_2$	6.42	–	–	2.49	Bal.
$Mg_{97}Zn_1MM_2$	–	6.80	2.83	2.59	Bal.

fatigue behavior [8]. Recently the rapidly solidified $Mg_{97}Zn_1Y_2$ has high strength and high corrosion resistance, and has therefore attracted considerable attention [9]. This alloy has excellent properties because of not only the refinement of the magnesium matrix to a size of 0.1–0.2 μm but also the fine precipitates with a long-period stacking ordered (LPSO) structure [10]. Therefore, alloying magnesium with rare earth (RE) can be used to improve its mechanical properties. Although $Mg_{97}Zn_1Y_2$ includes an LPSO phase, but not all RE-containing magnesium alloys always contain LPSO phase. The LPSO phase that is formed during the solidification is classified as type I when Y, Dy, Ho, Er or Tm is added and type II when Gd or Tb is added. Mg-RE compounds, rather than the LPSO phase, are formed during solidification and the 14H LPSO phase is precipitated by annealing [10,11]. Some magnesium alloys that contain some RE elements, such as La, Ce, Nd and Pr, can be classified as non-LPSO alloys [12]. The coexistence of Mg-RE second phases can greatly improve the mechanical properties of rapidly solidified non-LPSO Mg–Zn–La and Mg–Zn–Ce alloys [13]. Although the strengthening effect of the LPSO phase has been studied, the hardening mechanism of second phase-containing non-LPSO alloys has rarely been elucidated.

In this study, lower-cost La-rich mischmetal (MM) was added to magnesium alloys to increase their strength. The $Mg_{97}Zn_1MM_2$ was produced by a conventional ingot metallurgy process. For comparison, $Mg_{97}Zn_1Y_2$ was made by the same method as was used to make. The strengthening mechanism and mechanical properties of both alloys were systematically investigated.

2. Experimental

$Mg_{97}Zn_1MM_2$ and $Mg_{97}Zn_1Y_2$ were melted by the vacuum induction melting of highly pure Mg, Zn, Y and MM (71 wt.%La, 28 wt.%Ce with some minor elements of Nd and Pr) metals in an iron crucible, and then cast in a steel mold with a diameter of 180 mm and a length of 400 mm in an Ar atmosphere. Following homogenization treatment at 773 K for 10 h, the ingots were extruded into plates with a thickness of 5 mm and a width of 120 mm at an extrusion temperature of 673 K. Hot rolling at 773 K was carried out to modify the microstructures of the alloys. The compositions of as-extruded $Mg_{97}Zn_1MM_2$ and $Mg_{97}Zn_1Y_2$ were analyzed by ICP-AES and shown in Table 1.

Table 2
Mechanical properties of as-extruded $Mg_{97}Zn_1Y_2$ and $Mg_{97}Zn_1MM_2$.

	$Mg_{97}Zn_1Y_2$	$Mg_{97}Zn_1MM_2$
UTS (MPa)	350	250
YS (MPa)	209.6	225.6
EL (%)	15.5	6.1

The microstructures of the alloys were examined by optical microscopy (OM), X-ray diffractometry (XRD), scanning electron microscopy (SEM; Hitachi S-3400N) and transmission electron microscopy (TEM: JEOL JEM-2100F). The TEM specimens were prepared by ion milling at 4 kV. Tensile tests were carried out using a Shimadzu AG-I tensile test machine with an initial strain rate of 1×10^{-3} s^{-1}. The tensile test specimens with gauge dimensions of 6 mm in width and 10 mm in length were formed using a punch machine.

3. Results and discussion

Fig. 1 presents OM images of as-extruded $Mg_{97}Zn_1MM_2$ and $Mg_{97}Zn_1Y_2$ alloys. The extrusion direction is in the horizontal in all figures herein. The α-Mg matrix was dynamically recrystallized owing to extrusion at high temperature. Furthermore, the second phases in the $Mg_{97}Zn_1MM_2$ and $Mg_{97}Zn_1Y_2$ alloys were also refined to sizes of 2~5 μm and 5–12 μm, respectively. The second phase in the $Mg_{97}Zn_1MM_2$ alloy is inferred to have been easily refined following extrusion. From the tensile test results shown in Table 2, the tensile test results revealed that the yield strength (226 MPa) of the as-extruded $Mg_{97}Zn_1MM_2$ alloy exceeded that (210 MPa) of $Mg_{97}Zn_1Y_2$ alloy, whereas the elongation (15.5%) of the as-extruded $Mg_{97}Zn_1Y_2$ alloy exceeded that (6.1%) of the $Mg_{97}Zn_1MM_2$ alloy. To determine why the $Mg_{97}Zn_1MM_2$ alloy had the higher yield strength, the microhardness of the matrix and that of the second phases were measured. According to the micro Vickers results and the hardness indentations that are shown in Fig. 1, the matrices of both alloys had very similar microhardnesses indicating that the difference between the solubilities of the solutes in the matrices of both alloys did not result in a significant difference in hardness. However, the microhardness of the second phase in $Mg_{97}Zn_1MM_2$ alloy is 146.2 HV, which greatly exceeds that (86.9 HV) of the second phase in $Mg_{97}Zn_1Y_2$ alloy. The high hardness of the second phase in $Mg_{97}Zn_1MM_2$ alloy is inferred to increase its yield strength.

The SEM/BEI images reveal that $Mg_{97}Zn_1MM_2$ and $Mg_{97}Zn_1Y_2$ alloys each have two phases. A quantitative analysis of the EDS results indicates that the second phases are (La, Ce)$(Mg,Zn)_{12}$ and $Mg_{12}ZnY$ (LPSO) in the $Mg_{97}Zn_1MM_2$ and $Mg_{97}Zn_1Y_2$ alloys,

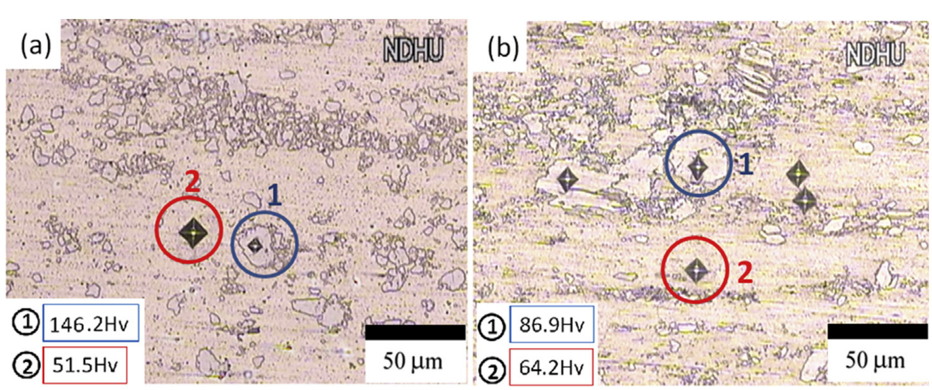


Fig. 1. Microstructures and hardness indentations of as-extruded $Mg_{97}Zn_1MM_2$ (a) and $Mg_{97}Zn_1Y_2$ (b).