Journal of Alloys and Compounds 646 (2015) 431–436

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

Effect of aging temperature on precipitation behavior and mechanical properties of extruded AZ80-Ag alloy

Shilun Yu [a], Yonghao Gao [a, *], Chuming Liu [a], Xiuzhu Han [b]

[a] School of Materials Science and Engineering, Central South University, Changsha 410083, China
[b] Aerospace Research Institute of Materials and Processing Technology, Beijing 100076, China

ARTICLE INFO

Article history:
Received 27 March 2015
Received in revised form
12 June 2015
Accepted 16 June 2015
Available online 18 June 2015

Keywords:
Magnesium alloy
AZ80-Ag
Aging behavior
Microstructural evolution
Precipitates
Mechanical properties

ABSTRACT

Aging behavior and related microstructural evolution of AZ80-Ag alloy as a function of aging temperature are systematically investigated. Results show that Ag addition can significantly enhance the age-hardening response of AZ80, improving its peak hardness and shortening the time to reach the peak simultaneously. Two kinds of continuous precipitates and three kinds of discontinuous precipitates are observed under varying conditions. The volume fraction ratio of continuous precipitates to discontinuous precipitates increases with increasing aging temperature. When aged at 175 °C for 38 h, the whole microstructure is invaded by discontinuous precipitates and an ultimate tensile strength of 428 MPa is achieved.

1. Introduction

The great significance of weight reduction in aerospace and transport industries has been stimulating the development of magnesium alloys due to their low density and high specific strength compared with other metallic materials [1–4]. Among various magnesium alloys, AZ80 is applied in a relatively wider area owing to its excellent combination of comparatively low cost, moderate strength and reasonable plasticity [5]. Recently, new efforts have been devoted towards strength enhancement in AZ80 alloy to expand its applications to areas where higher strength is concerned, and many methods have been proposed, of which micro-alloying is an effective one. Payne et al. [6] reported that addition of Ag could improve the tensile properties of Mg–Nd alloys. After this pioneering work, extensive studies have been conducted to explore the mechanism governing this strength increment by Ag addition, and it is now generally acknowledged that the enhanced age-hardening response might be responsible, as reported by Yamada et al. [7] in Mg–Gd alloy and Zhu et al. [8] in Mg–Y–Zn alloy, where the improvement was attributed to the formation of densely distributed basal plate-shaped precipitates that were not observed in the Ag-free alloy. However, the effect of Ag addition into AZ80 has drawn little attention to date. Thus, in order to further improve the strength of AZ80, it is of great significance to explore the potential of strength enhancement in AZ80 alloy by adding appropriate amount of Ag. This paper aims to investigate the effect of Ag on the aging kinetics of the AZ80 magnesium alloy and mainly focuses on the microstructure evolution as a function of aging temperature, especially the changes of precipitates morphologies in the Ag-containing AZ80 magnesium alloy (denoted as AZ80-Ag hereafter).

2. Experimental procedures

The materials studied in this paper were provided by HEBI WONDERFUL Magnesium Technology Co., Ltd. and received in the form of extruded plate with a dimension of 60 mm × 150 mm × 1000 mm, and the measured chemical compositions are shown in Table 1. Samples for investigation were machined from the plate and solution treated in a resistance furnace at 415 °C for 3 h followed by water quenching. Subsequently, all the samples were divided into four groups for aging treatment, performed in an air furnace, at different temperatures, i.e. 175 °C, 250 °C, 300 °C and 350 °C. For each set of parameters, three parallel samples were prepared to guarantee the reliability of the obtained data. During

* Corresponding author.
E-mail address: gaoyonghao_009@163.com (Y. Gao).

http://dx.doi.org/10.1016/j.jallcom.2015.06.126
0925-8388/

Table 1
Measured chemical compositions of as-received alloys (wt.%).

Alloy	Mg	Al	Zn	Mn	Ag	Cu	Fe	Ni
AZ80-Ag	Bal.	7.80	0.46	0.19	0.50	≤0.002	≤0.001	≤0.002
AZ80	Bal.	7.85	0.45	0.20	–	≤0.002	≤0.001	≤0.002

the whole process of heat treatment, the temperature fluctuation was controlled within ±3 °C.

Age-hardening response was determined using Vickers hardness tests, which were conducted with a load of 4.9 N and dwelling time of 15 s. To ensure the reliability of the tests, 10 indentations were measured for each test. Microstructure was characterized by Leica optical microscopy (OM) and FEI Sirion 200 scanning electron microscopy (SEM), and the observation plane was perpendicular to the extrusion direction. Samples for both OM and SEM observation were mechanically ground and polished, followed by etching in an alcohol solution containing 4% HNO_3. Phase analysis was conducted on D/Max2500 X-ray diffractometer (XRD) with a CuKα radiation (λ = 0.154 nm), operated at 36 kV in a 2Theta range of 10–80°. Tensile tests were performed on an Instron 3369 tester following the ASTM B557M–94 standard with the tensile direction parallel to the extrusion direction.

3. Results and discussions

3.1. Solution treatment and aging response

The AZ80 alloy with and without Ag addition present similar optical features (grain size, precipitates morphologies and distribution, etc.), therefore only that of AZ80-Ag alloy is shown here in Fig. 1. Massive net-like intermetallics, which are proven to be β-$Mg_{17}Al_{12}$ using XRD examination (Fig. 2), are distributed along the grain boundaries in the as-extruded sample (Fig. 1(a)). After solution treatment, almost all of the net-like β-$Mg_{17}Al_{12}$ are dissolved into the α-Mg matrix and the grain boundaries become straight and clear, as shown in Fig. 1(b). However, the grains coarsen slightly from ~30 μm to ~35 μm during the solution treatment. The XRD results (Fig. 2) also demonstrate the dissolution of β-$Mg_{17}Al_{12}$ phase, which is consistent with the metallographic observation.

Fig. 3(a) exhibits the age-hardening response of AZ80-Ag magnesium alloy aged at different temperatures. The age-hardening effect varies as a function of aging temperature. Hardness of samples aged at 175 °C and 250 °C increases rapidly in the initial stage of aging treatment and obtains an obvious increment when reaching the peak. Nonetheless, samples aged at 300 °C and 350 °C only obtain a comparatively weak hardening effect, especially for the 350 °C-aged sample. After reaching the peak, hardness of all the tested samples becomes stable, without obvious decrease within the examined time range. Fig. 3(b) shows the comparison between the aging behavior of AZ80 and AZ80-Ag alloy aged at 175 °C. For the AZ80 alloy, 51 h are taken to achieve the peak hardness of 82 HV, while the time is significantly shortened to 38 h for the AZ80-Ag alloy and the peak-aged hardness increases by 8 HV to 90 HV, indicating that Ag addition can significantly accelerate the aging kinetics and simultaneously improve the peak-aged hardness of AZ80 magnesium alloy. Apart from the micro-alloying of Ag, there is no other distinct difference between the AZ80 and AZ80-Ag alloy studied in the present work. Consequently, the enhancement of age-hardening response can reasonably be attributed to the Ag addition. Similar effects of Ag addition have been reported in Mg–Y–Zn series [8], Mg–Gd series [7,13] and Mg–Sn–Mn series magnesium alloys [14]. However, different from the studies in Mg-RE series alloys [7,8,13] where the formation of densely distributed basal precipitates was observed and in Mg–Sn–Mn alloy [14] where a newly formed intermetallic $Mg_{54}Ag_{17}$ was found, XRD examination results indicate that there does not exist any newly formed phase in the AZ80-Ag alloy investigated in this work (Fig. 2). Thus, the hardening mechanism of Ag in the present study might differ from those reported in Mg-RE series magnesium alloys. According to reference [14], the possible reason for the peak-hardness enhancement brought about by Ag addition might be that Ag atoms in the supersaturated solid solution promote the nucleation of strengthening precipitates by providing sites for heterogeneous nucleation, thus refining the precipitate size. Whether this hypothesis also applies to the AZ80-Ag alloy will be experimentally verified in our following studies.

3.2. Microstructure evolution

As the dominant strengthening phase in Mg–Al series alloys, β-$Mg_{17}Al_{12}$ precipitates out directly from the supersaturated α-Mg matrix, continuously or discontinuously [15]. And according to their morphologies, the β phase in Mg–Al alloys can be easily classified into two types, i.e. continuous and discontinuous precipitates, which occur simultaneously or competitively with each other [16]. For the continuous precipitates (CP), there are two possible morphologies including lath-shaped and rhombic ones, while there exist three kinds of morphologies involving cellular structure, oval-shaped particles and intergranular precipitates for the discontinuous precipitates (DP) [10].

Microstructures of the 175 °C-aged AZ80-Ag sample are shown in Fig. 4. When aged for 30 h (Fig. 4(a)), most grains are invaded by lamellar precipitates, i.e. so-called cellular structure. Besides, many oval-shaped precipitates with an equivalent diameter of ~0.3 μm are observed nearby the interfaces between cellular structure and α-Mg matrix, shown in the image embedded in Fig. 4(a). It can be seen that there still exists some residual α-Mg matrix in 30-h-aged sample (unoccupied black area in Fig. 4(a)). Features of sample held for 38 h at 175 °C are shown in Fig. 4(b). The unoccupied area in Fig. 4(a) has been completely invaded by lamellar precipitates, and the growth direction of the lamellae in the interior of each grain is nearly parallel but differs from that within other grains. The two types of precipitates mentioned above are typical morphologies of discontinuous precipitates.

Different from the microstructure of 175 °C-aged sample, plenty of lath-shaped and irregular rhombus precipitates appear in the sample aged at 250 °C (marked as CP in Fig. 5(a)). Precipitates in possession of these two types of morphologies are typical continuous precipitates in Mg–Al series alloys, and Fig. 5(b) is a closer observation for the CP in 250 °C-aged AZ80-Ag sample. The irregular rhombus precipitates are usually called Widmannstatten structure [9]. These two kinds of precipitates are oriented in different ways. The irregular rhombus ones are arranged at an angle (~60°) to each other (Fig. 5(c)), while the lath-shaped precipitates are parallel to each other and highly oriented in one single direction within each individual grain (Fig. 5(d)). With the increase of continuous precipitates, volume fraction of discontinuous precipitates (mainly referring to cellular structure) decreases significantly. Oval-shaped particles, distributed at the vicinities of grain boundaries and lamellae, are also observed in Fig. 5(a). In addition, along the grain boundaries, many intergranular precipitates are formed, illustrated by the red (in the web version) line pairs in Fig. 5(a) and (b). Besides, it is interesting to note that instead of coexisting with each other, there are distinct interfaces between domains occupied by continuous and discontinuous precipitates.

When aging temperature is raised to 300 °C, microstructure has been altered, as shown in Fig. 6. Volume fraction of cellular structure is further reduced, fine continuous precipitates occupy the