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Aging behavior of Mg-Li-Al alloys①

Ma Chunjiang(马春江), Zhang Di(张 荻), Qin Jining(覃继宁),
Hu Wenbin(胡文彬), Shi Zhongliang(施忠良)
State Key Lab of MMCs, Shanghai Jiao Tong University,
Shanghai 200030, P. R. China

Abstract: A system study on aging behavior and the influence of heat treatment on mechanical property of Mg8Li1Al and Mg11Li3Al alloys has been carried out. The results show that the alloys described above have apparent aging behavior and over aging happens even at room temperature. $\theta(\mathrm{MgLi_2Al})$ phase has been identified when hardness reaches aging peak. With the increase of aging temperature, the size of $\theta(\mathrm{MgLi_2Al})$ phase becomes larger apparently and over aging happens. Heat treatment can raise tensile strength of Mg8Li1Al and Mg11Li3Al alloys, but the elongation decreases greatly.

Key words: Mg-Li-Al alloys; aging; mechanical property **Document code:** A

1 INTRODUCTION

Magnesium alloys have been found wide application in airplane and automobile industry, because of its low density and the high specific strength and specific modulus. However, the poor ductility of magnesium confined its application field, because of the hcp magnesium structure. In order to improve the ductility of magnesium alloys, Mg-Li alloys were developed successively by some countries such as America, England and Japan. Adding lithium with a density of 0.53 g/cm^3 into magnesium could not only lower the density, increase the specific strength and specific modulus, but also lower the ratio(c/a) of hcp magnesium. As a result, Mg-Li alloys can slide not only in $\{0001\}$, but also in $\{1011\}$ or $\{1010\}$[1,2]. When the content of lithium increased over 5.5 %, a cubic phase called β phase which possesses good plasticity appeared and therefore Mg-Li alloys showed good ductility[3~8]. Neverthelessly, the Mg-Li alloys with high content of lithium showed lower tensile strength and were apt to creep even at room temperature[3,9]. In order to increase the strength and the creep resistance, many authors attempted to add third alloying elements to Mg-Li alloys to strengthen the matrix. The results show that the tensile strength of Mg-Li based alloy is increased apparently, however, the ductility is decreased. Moreover, the Mg-Li based alloy with more than three element is unstable both in microstructure and mechanical properties. Overage phenomena was found even at room temperature[10,11], however, some questions such as the precipitation behavior and the reason of overage for Mg-Li-Al alloys still remain. The purpose of this paper is to study the aging behavior and the mechanism of overage aspects of Mg-Li-Al alloys.

2 EXPERIMENTAL

2.1 Alloy preparation

The row materials were Mg(99.9%), Li (99.95%) and Al(99.99%). Mg8Li1Al and Mg11Li1Al alloys were prepared by heating solid pieces of magnesium, lithium and aluminum in a tall steel tube in an electric furnace. In order to keep the melt from oxidation, the melt was covered with LiCl flux and the entire operation was carried out in a high pure argon atmosphere. After being suitably superheated, the melt was allowed to solidify in a steel mould. In this way,

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ingots with a size of *d* 50 mm × 100 mm were fabricated. The composition of Mg-Li-Al alloys is presented in Table 1.

Table 1 Compositions of Mg-Li-Al alloys(%)

Specimen	Li	Al	Mg
Mg8Li1Al	8.6	1.36	Balance
Mg11Li3Al	10.6	2.8	Balance

2.2 Heat treatment and hardness testing

In order to keep the Mg-Li-Al alloys from oxidation, specimens were solution treated in a sealed silicon tube evacuated to 1.3 Pa and then back filled with high pure argon to 45.3 kPa. Specimens were heated at 350 ℃ for 1 h and then quenched into ice water. All the solution treated specimens were kept in a refrigerator at − 30 ℃ in order to avoid the specimens from aging at room temperature until they were used for experiment. Aging tests were carried out at room temperature and at 80 ℃ respectively. In order to study the aging behavior of Mg-Li-Al alloys, a Vickers hardness tester was used. The load employed was 10 N and maintained for 15 s. The hardness values reported in this paper are the average of five measurements.

2.3 Microstructure observation and tensile test

The specimen microstructure was examined by optical microscope. All the specimens used for microstructure observation had to be polished and then etched with nitric acid alcohol. The precipitate of the alloy was determined by X-ray diffraction (XRD) techniques.

In order to study the influence of aging hardening on mechanical properties, tensile test was carried out using an Instron tensile tester with a strain rate 8.3×10^{-4}/s. Tensile specimens were machined with a gauge length of 15 mm and a cross section of 1.5 mm × 4 mm. JSM-6400 scanning electron microscope (SEM) was employed to observe the fracture morphology of the specimen.

3 RESULTS AND DISCUSSION

3.1 Hardness curves

Fig.1 and Fig.2 show typical hardness variations aged at room temperature and at 80 ℃ respectively for the Mg8Li1Al and Mg11Li3Al alloys. As shown in Fig.1, after being solution treated, the hardness of Mg8Li1Al alloy increases quickly and attains its maximum value within 4 h. After 100 h, a slight decrease in hardness is observed. On the other hand, compositions of Mg-Li-Al alloys have apparent influence on aging peak hardness and aging dynamics. For the Mg8Li1Al alloy, the maximum hardness varies between 80 ~ 85. For the Mg11Li3Al alloy, however, the peak hardness increases to 115 ~ 120, which is two times of the value of as-cast specimen. Moreover, the hardening rate of Mg11Li3Al alloy is higher than that of Mg8Li1Al alloy. The hardness of Mg11Li3Al alloy attains its peak value within only 1 h. However, Mg11Li3Al alloy is unstable and shows decrease in hardness after 60 h.

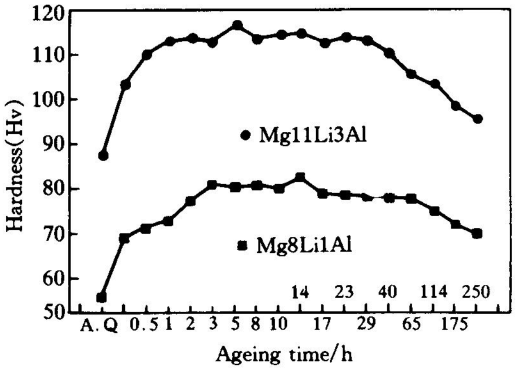

Fig.1 Aging curves aged at room temperature

With the increase of aging temperature (Fig. 2), the peak values of hardness become lower and the time for the peak to appear becomes sooner for the Mg8Li1Al and Mg11Li3Al alloys. Moreover, overage was observed within much shorter time.

3.2 Precipitation mechanism and XRD analysis

It is generally believed that the age-hardening phenomena of Mg-Li-Al connects with a metastable phase called θ($MgLi_2Al$) which precipitates in the β matrix and strengthens the

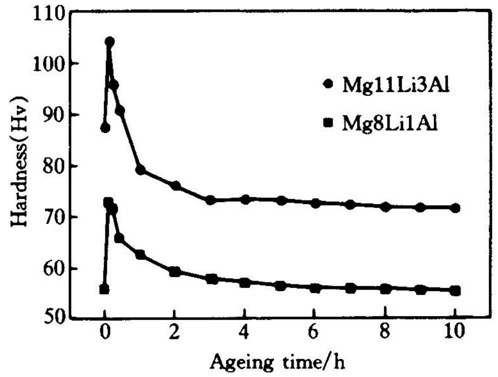

Fig.2 Aging curves aged at 80 ℃

alloy. However, θ($MgLi_2Al$) is unstable and finally transforms to stable AlLi phase. As a result, overage occurs and the hardness loses[10~13]. Fig. 3 is XRD patterns of Mg8Li1Al alloy. It has been detected that the as-cast Mg8Li1Al alloy consists of two-phase structure ($\alpha + \beta$), in which α phase is solid solution of magnesium with low lithium content and retains the hcp structure, β phase is solid solution of lithium with magnesium. After aging at room temperature for 40 h, diffraction peaks of θ($MgLi_2Al$) which had a complex cubic structure[11] were identified. Comparing Fig. 1 with Fig.3, it can be confirmed that the strengthening phase is θ($MgLi_2Al$). In order to identify the crystal structure of precipitates, transmission electron microscope was employed, however, the lithium was so active and lost during the preparation of TEM specimen, therefore the identification of precipitate was frustrated. Fig.4 is XRD patterns of Mg8Li1Al alloy which was solution treated and aged for 1 h at room temperature, 50 ℃, 100 ℃ and 150 ℃ respectively. It was found that, there is no θ($MgLi_2Al$) peak in the XRD pattern for the specimen aged for 1 h at room temperature; when the aging temperature increases to 50 ℃, a clear θ($MgLi_2Al$) peak has identified, this also confirms that the strengthening phase is θ($MgLi_2Al$); however, with the increase of aging temperature, when overage occurs, θ phase still exists. These results are in conflict with those reported by Jones[14,15].

According to Refs. [14, 15], overage of Mg-Li-Al alloy contributes the precipitation of stable AlLi phase. Neverthelessly, according to this paper there is no AlLi phase precipitation when overage occurs.

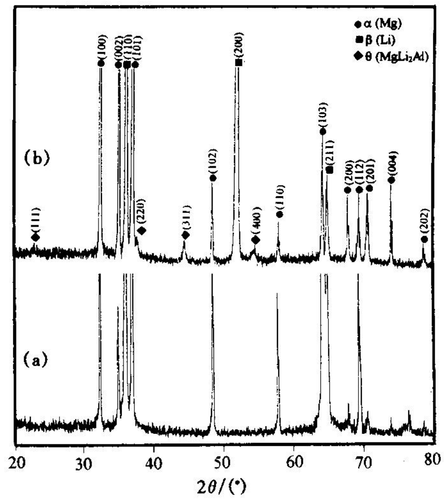

Fig.3 XRD patterns of Mg8Li1Al alloy
(a)—Solution treated; (b)—Aged at room temperature for 40 h

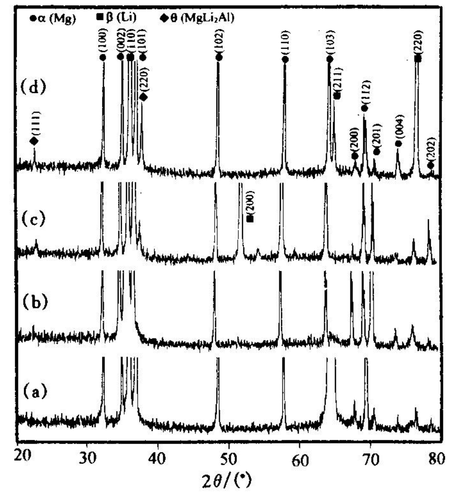

Fig.4 XRD patterns of Mg8Li1Al alloy aged at different temperatures for 1 h
(a)—Room temperature; (b)—50 ℃; (c)—100 ℃; (d)—150 ℃

Fig.5 shows the optical microstructures of Mg8-Li1Al alloy aged for 1 h at room temperature, 50 ℃, 100 ℃ and 150 ℃. Fig.5(a) shows $(\alpha+\beta)$ two phases structure, in which α phase disperses uniformly in the β phase. When aging temperature increases to 50 ℃, large quantity of fine precipitates in β matrix and on the interface of α phase and β phase are found. With the increase of aging temperature, the size of precipitate becomes larger, which is coordinate with the θ diffraction peak in Fig.4.

Comparing the aging curves with XRD patterns and microstructure of Mg8Li1Al alloy, it can be concluded that the aging phenomena is caused by the precipitation of θ ($MgLi_2Al$) phase. However, θ ($MgLi_2Al$) phase dose not disappear and there is not AlLi phase precipitation when overage occurrs. As a result, overage can not be contributed to the precipitation of AlLi phase. However, the mechánism of overage has not been revealed clearly. According to the differences among the θ-lattice parameters at early aging stage with the overage stage[11], it can be speculated that coherency relation exists between the θ phase and β matrix. With the increase of time and temperature, θ-lattice parameter changes, the coherent relation is destroyed and overage occurrs.

3.3 Tensile properties

Fig. 6 is tensile curves of Mg8Li1Al and Mg11Li3Al alloys. Fig.7 is tensile fracture morphologies of Mg8Li1Al and Mg11Li3Al alloys. The mechanical properties are presented in Table 2. As observed in Table 2 and Fig.6, it is obvious that the as-cast Mg8Li1Al and Mg11Li3Al alloys show good ductility. The tensile elongation of Mg8Li1Al and Mg11Li3Al alloys can attain 35% and 45% respectively. Moreover, Mg11Li3Al alloy with high percent of lithium

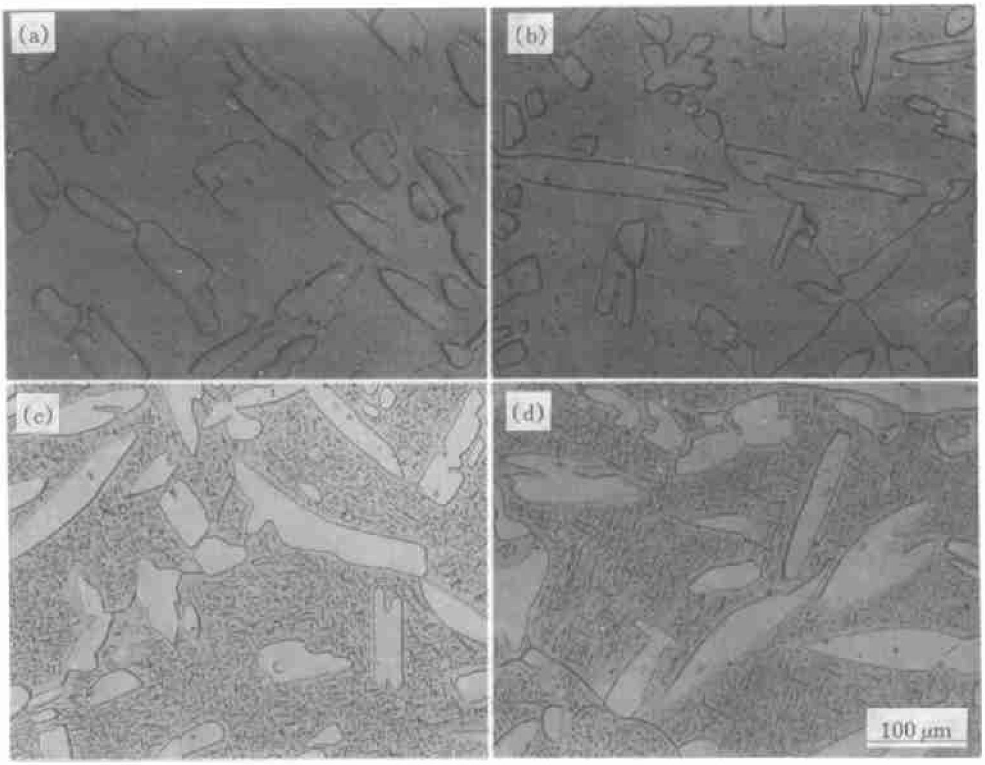

Fig.5 Optical microstructures of Mg8Li1Al alloy aged for 1 h at different temperatures
(a)—Room temperature; (b)—50 ℃; (c)—100 ℃; (d)—150 ℃

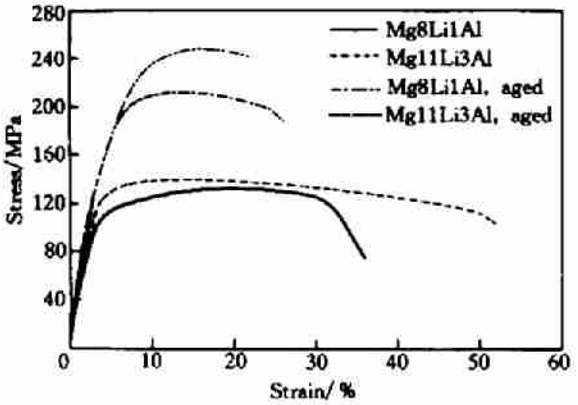

Fig. 6 Tensile curves of Mg8Li1Al and Mg11Li3Al alloys of as-cast and aged at room temperature for 40 h

Table 2 Tensile properties of Mg8Li1Al and Mg11Li3Al alloys

Alloys	UTS/MPa		Elongation/%	
	as-cast	heat treated	as-cast	heat treated
Mg8Li1Al	131	214	35	12
Mg11Li3Al	138	247	45	7

and aluminum possesses higher yield strength and the ultimate strength than those of Mg8Li1Al alloy. After being solution treated and aged at room temperature for 40 h, the yield strength and ultimate strength increased obviously. However, the elongation of Mg8Li1Al alloy decreased to 12%, while that of the Mg11Li3Al alloy decreased to 7%, apparently lower the values of as-cast alloy. In Fig. 7, the as-cast Mg8Li1Al and Mg11Li3Al alloys show typical plastic fracture which present large quantity of dimples. More-

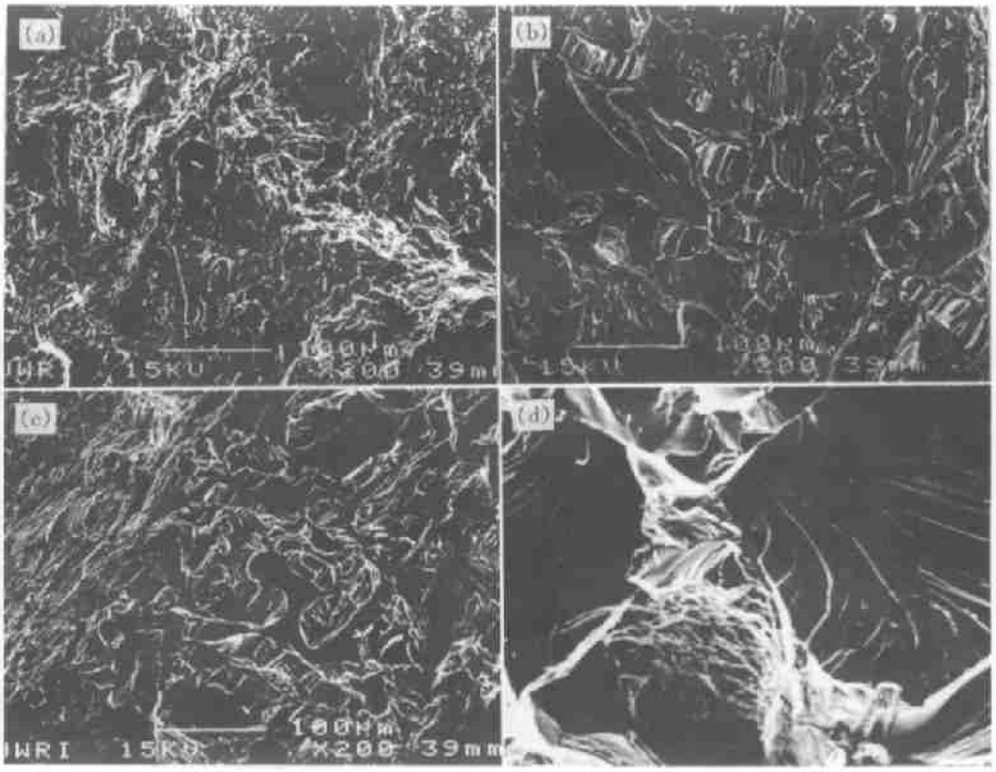

Fig. 7 Tensile fracture morphologies of Mg8Li1Al and Mg11Li3Al alloys
(a)—As-cast Mg8Li1Al; (b)—As-cast Mg11Li3Al; (c)—Aging treated Mg8Li1Al;
(d)—Aging treated Mg11Li3Al

over, tensile specimen presents uniformly deformation. After solution and aging treatment, the dimples in the Mg8Li1Al tensile fracture decrease, but plastic fracture character still exists. However, apart from small quantity of dimples, the tensile fracture of solution and aging treated Mg11Li3Al alloy present fragile character, it may contribute the high content of lithium and aluminum which formed more precipitate in the grain boundaries. As a result, the alloy fractures along the grain boundaries.

4 CONCLUSIONS

(1) Mg8Li1Al and Mg11Li3Al alloy show apparent aging phenomenon. With the increase of lithium and aluminum content, aging effect becomes stronger. However, Mg-Li-Al system is unstable and shows overage phenomena, especially for the Mg11Li3Al alloy.

(2) θ($MgLi_2Al$) phase is identified when Mg8Li1Al alloy reaches its maximum hardness. Neverthelessly, the θ($MgLi_2Al$) phase still exists and there is not AlLi phase precipitation when overage occurs. It comes to the conclusion that overage can not be account for the transformation of θ($MgLi_2Al$) to AlLi phase.

(3) The as-cast Mg8Li1Al and Mg11Li3Al alloys present good tensile elongation. The yield and ultimate tensile strengthes of Mg8Li1Al and Mg11Li3Al alloys are increased greatly by solution and aging treatment, but the elongation is decreased apparently, especially for Mg11Li3Al alloy. With the increase of aluminum content, the plastic fracture changes to fragile fracture after solution and aging treatment.

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