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ARTICLE

Microstructure and Mechanical Properties of as-Cast Mg-Li-Al-*x*Si Alloys

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Abstract: As-cast Mg-9Li-3Al-*x*Si（x=0, 0.1, 0.5, 1.0, wt%）alloys were prepared and then investigated by optical microscope (OM), scanning electron microscope (SEM) and X-ray diffractometer (XRD) and mechanical properties test. Results show that the as-cast Mg-9Li-3Al alloy consists of α-Mg, β-Li and $Mg_{17}Al_{12}$ phases. The addition of Si leads to the formation of new phase (Mg_2Si) and the refinement of the grain size. Moreover, Si addition can restrain the formation of $Mg_{17}Al_{12}$. However, when the content of Si is excessive, α-Mg phase will be coarsened and Chinese script Mg_2Si phase is formed in the phase boundary. The tensile strength of alloys initially increases and then decreases while the elongation decreases monotonically with the increase of Si content. Specifically, as-cast Mg-9Li-3Al-0.1Si shows a favorable combination of ductility and strength with an ultimate tensile strength of 182.5 MPa, yield strength of 136.8 MPa, and an elongation of 12.1%.

Key words: magnesium alloy; microstructure; mechanical properties; silicon

The demand for lightweight structural materials is fueled by the strategic requirement of reducing the greenhouse gas emissions and energy consumption[1,2]. Mg alloys, with merits of low density, excellent physical and mechanical properties, have been paid much attentions to in recent years[3]. However, due to their hcp crystalline structure and high axial ratio (c/a) 1.6236, the deformation capacity of Mg alloys is relatively poor. For example, the elongation of commonly used as-cast AZ31 and AM60 are 4.8% and 3.0%, respectively, which consequently hinders the application of Mg alloys in many fields. Li additions to Mg have been reported to not only reduce the density, but also improve the ductility. Li additions decreases c/a axial ratio, even changes the crystalline structure of Mg alloys[4], which is beneficial to the improvement of ductility. Hence, Mg-Li alloys shows wide application prospects in the aircraft, airspace and military industry[4-8]. However, the strength of Mg-Li alloys is low. For example, the tensile strength of LA141 (Mg-14Li-1Al) alloy is only 138 MPa. Thus the extensive application of Mg-Li alloys is restricted.

According to Mg-Li binary phase diagram, α-Mg with hcp lattice and β-Li with bcc lattice coexist in Mg-Li alloys when the content of Li is between 5.7 wt%~10.3 wt%. α-Mg phase of Mg alloys is beneficial to the strength while β-Li phase is good to the ductility. Therefore, dual-phase Mg-Li alloys attract more and more attention. Thus, dual-phase Mg-Li alloy is focused in this research.

Improving the mechanical properties of Mg-Li alloys via alloying elements such as Al, Mn, Sr and Y is an effective way being studied[9,10]. With the addition of Al, the mechanical properties of Mg-Li alloy can be significantly improved due to its high solid solubility and density in Mg. However, the strength of Mg-Li-Al alloy remains limited. Therefore, it is necessary to introduce some other elements. Si with relatively low price and low density (2.33 g/cm^3) has been used to improve the mechanical properties of Mg-Li-Al alloys. Si mainly exists in the form of Mg_2Si intermetallic compound because its solubility in Mg is only

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0.003%, according to the phase diagram of Mg-Si. Mg_2Si possesses high melting point (1085 ℃), high hardness HV (4600 MPa), high elasticity modulus (120 GPa), low density and low thermal expansivity (7.5×10^{-6} K^{-1}) [11,12]. Therefore, adding Si is an effective way to improve the microstructure and mechanical properties of Mg-Li alloy[13-17]. However, if Mg_2Si appeared with blocky structure or in Chinese character shape, it will greatly worsen the mechanical properties of alloy[12,16]. Therefore, the key aim of current researches is to control the size, shape and distribution of Mg_2Si in alloy. Currently, there are few reports about how to obtain small and dispersed Mg_2Si. This paper explored an economical way to improve the comprehensive mechanical property of Mg-Li alloy by adding a small amount of Si, which will broaden the application area of Mg-Li alloy.

1 Experiment

The starting materials used in this study are pure Mg (99.99%), pure Li (99.99%), pure Al (99.99%) and Mg-10Si master alloy. Target alloys were melted in a melting furnace under the protection of argon atmosphere. Firstly, the materials were put into graphite crucibles. Then they were heated to 720 ℃. Subsequently, raising the temperature to 780 ℃, Al and Mg-10Si were added into liquid magnesium and maintained for 20 min. Then Li was added at the temperature 720 ℃ for 10 min. Finally, the liquid alloy was poured into metal molds (Φ90 mm×50 mm) to form the as-cast alloy ingots.

The specimens were cut from the center of the as-cast ingots. The samples were prepared using standard mechanical grinding and polishing procedures followed by etching using 2% nital. Then microstructure was observed by optical microscope (Olympus), scanning electron microscope (SEM, JOEL/JSM-6460LV) with X-ray energy dispersive spectrometer (EDS, Oxford) and X-ray diffractometer (XRD, D/MAX-A). In addition, tensile tests of the alloys were conducted at ambient temperature on an SANS CMT-5105 material testing machine with the speed of 2.0 mm/min.

2 Results and Discussion

2.1 Microstructure of alloys

Fig.1 shows the microstructure of as-cast Mg-9Li-3Al-*x*Si alloy. In the figure, the alloys consist of α-Mg phase and β-Li phase. The white area is α-Mg phase while the black is β-Li phase area. The white α-Mg of alloy in Mg-9Li-3Al alloy shows as a thick block with black particles inside as shown in Fig.1a.

With the increase of Si content, the grain size of α-Mg increases first and then decreases. When the content of Si is 0.1% (Fig.1b) and 0.5% (Fig.1c), the refinement of α-Mg is obvious and the distribution of α-Mg phase becomes more homogeneous. When Si content increases to 1.0% (Fig.1d), the grain size of α-Mg becomes larger. Besides, some black particles and new Chinese script phase are formed at phase boundaries.

The SEM images of as-cast Mg-9Li-3Al-*x*Si alloys are shown in Fig.2. The morphology of SEM is basically consistent with the result of optical microscope. The black lump one is α-Mg and the lighter area is β-Li. Some tiny white particle phases exist at the phase boundary of α/β. With the increase of Si, the grain of alloys are refined first and then coarsened while white particle phase gradually increases on the edge of α phase. When the content of Si is 0.5% (Fig.2c), a blocky white particle phase appears in alloy. When the content of Si increases to 1% (Fig.2d), the blocky white particle phase gets more and bigger. The preliminary speculation is that the formation of the white particles is related to Si. Hence, adding a certain amount of Si can refine the microstructure of alloys, but excessive amount will coarsen it.

Fig.3 shows the XRD patterns of as-cast Mg-9Li-3Al-*x*Si alloy. The XRD indicates that Mg-9Li-3Al alloy mainly consists of α-Mg, β-Li and $Mg_{17}Al_{12}$ phases. With the increase of Si content, new Mg_2Si phase appears with the gradual disappearance of $Mg_{17}Al_{12}$, which illustrates that Si restrains the formation of $Mg_{17}Al_{12}$. In Fig.3, the diffracted intensity of α-Mg declines while the diffraction peak intensities of β-Li and Mg_2Si gradually increases, which shows that the addition of Si decreases α-Mg slowly and increases

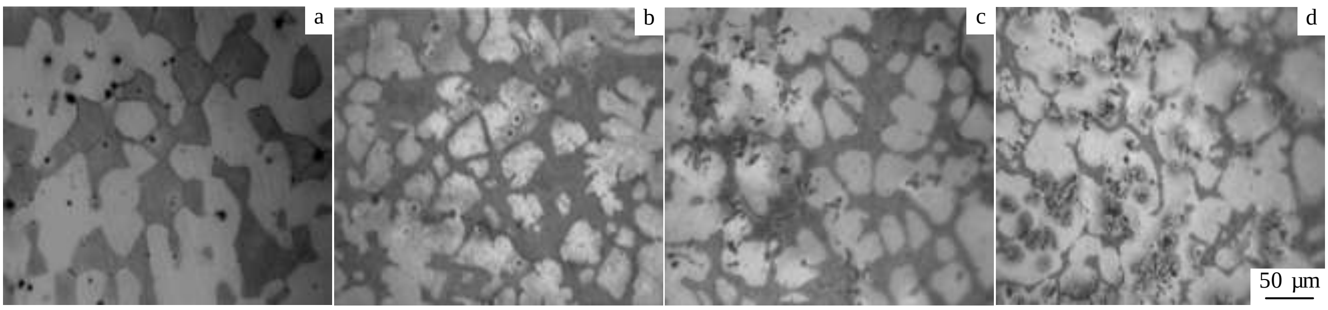

Fig.1 Microstructures of as-cast Mg-9Li-3Al-*x*Si alloys: (a) *x*=0, (b) *x*=0.1, (c) *x*=0.5, and (d) *x*=1.0

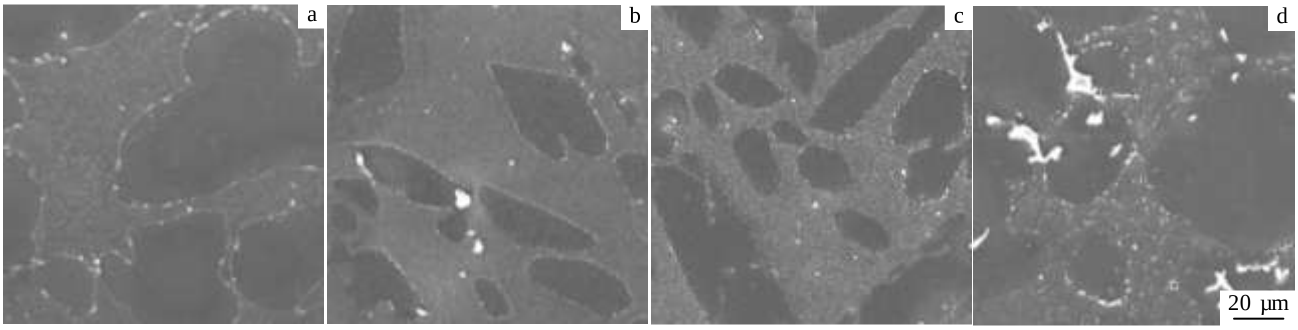

Fig.2 SEM images of as-cast Mg-9Li-3Al-xSi alloys: (a) x=0, (b) x=0.1, (c) x=0.5, and (d) x=1.0

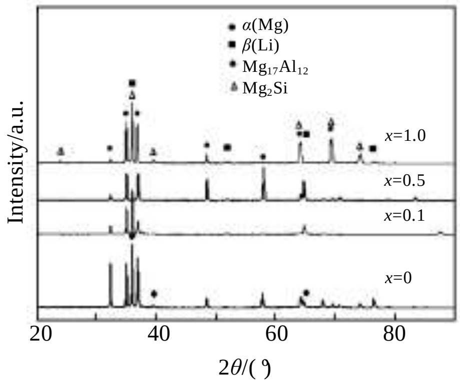

Fig.3 XRD results of as-cast Mg-9Li-3Al-xSi alloy

Mg_2Si gradually. The result accords with the previous analysis of alloy SEM morphology.

Further analysis is required to determine the white particle phase of Mg-9Li-3Al-xSi alloy. Fig.4 and Fig.5 show EDS analysis of as-cast Mg-9Li-3Al and Mg-9Li-3Al-0.5Si alloys, respectively. The EDS point analysis, conducted at specific locations labeled as A and B, shows the presence of Mg and Al element in this region. Spectrogram C and D mark the blocky white particles on the edge of α-Mg. As shown in Fig.5, the main elements in white particle phase are Mg, Al and Si and the mole ratio of Mg to Si at location C and D is approximately 2:1. Combined the EDS results (Fig.5) with the XRD results, it can be confirmed that the intermetallic compounds are mainly Mg_2Si.

As shown in Fig.1 and Fig.2, the α-Mg phase gets smaller first and then bigger, while the proportion of α-Mg phase keeps reducing with increasing Si content. This phenomenon can be explained by the refinement mechanism of Si. Firstly, Si with high melting point and low solubility in Mg, gathered in the forefront of the solid-liquid interface, which led to the formation of constitutional supercooling during the solidification of alloys. Consequently, the activated core of constitutional supercooling zone raised the nucleation rate in the interface, which is beneficial to grains refinement. Secondly, with the addition of Si, Mg_2Si with high

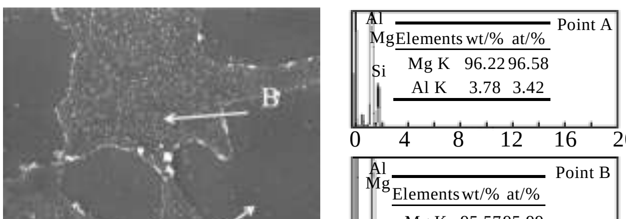

Fig.4 SEM morphology and EDS results of as-cast Mg-9Li-3Al alloy

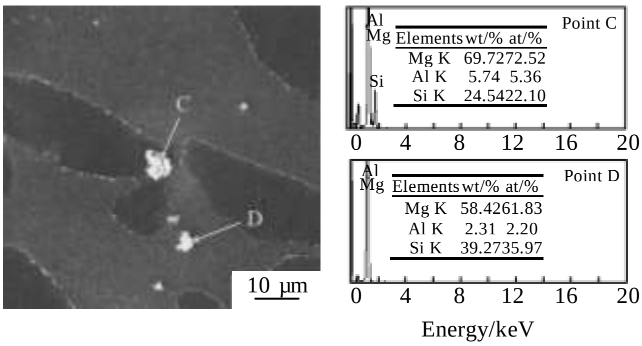

Fig.5 SEM morphology and EDS results of as-cast Mg-9Li-3Al-0.5Si alloy

melting point was formed at the phase boundary of α-Mg, hindering the growth of α-Mg grain. Therefore, when the content of Si is 0.1% or 0.5%, the α-Mg phases are obviously refined. But when the content of Si is 1.0%, Mg_2Si phase gets bigger, changing from dispersed particles to bulk or Chinese script shape which cannot effectively hinder the growth of α-Mg and dislocation moving.

2.2 Mechanical properties of Mg-9Li-3Al-*x*RE alloys

The mechanical properties of as-cast Mg-9Li-3Al-xSi alloys at room temperature are listed in Table 1. Fig.6 shows the influence of Si content on the mechanical properties of as-cast alloys.

Table 1 Mechanical properties of as-cast Mg-9Li-3Al-*x*Si alloys

x	$\sigma_{0.2}$/MPa	σ_b/MPa	δ_5/%
0	89.6	114.3	14.5
0.1	136.8	182.5	12.1
0.5	132.6	168.2	7.6
1.0	123.8	159.7	5.3

As shown in Table 1 and Fig.6, the addition of Si can improve the strength significantly with a little decrease of elongation. Both the yield strength and the tensile strength of alloys increase first and then decrease with the increase of Si content. Mg-9Li-3Al alloy with 0.1% Si addition has maximum tensile strength of 182.5MPa and yield strength of 136.8 MPa, with elongation of 12.1% (remaining relatively high), which is 59.6% and 52.6%, higher than Mg-9Li-3Al alloy, respectively. However, the further increase of Si content results in the reduction of tensile strength. Thus appropriate Si content can significantly improve the comprehensive mechanical properties of as-cast Mg-9Li-3Al alloy.

$Mg_{17}Al_{12}$ in Mg-9Li-3Al alloy is a kind of brittle phase, which is mainly distributed in the interface of α phase and β phase. It can cut apart the interface of α phase and β phase. That is why the strength of Mg-9Li-3Al alloy is relatively low[18]. With increasing of Si content, $Mg_{17}Al_{12}$ phase will be replaced by Mg_2Si phase gradually. Then α-Mg, as a strengthening phase, becomes finer and more homogeneous so that strength initially increases. In addition, Mg_2Si, as one of high temperature hard phases, distributes in the interface of α phase and β phase as particles or small strips. It can effectively hinder the movements of dislocations, which is beneficial to the improvement of mechanical properties. Therefore, the comprehensive mechanical property of Mg-9Li-3Al-0.1Si alloy is the best.

However with further increase of Si content, the strength of alloys decreases. The reason is that when the content of Si is excessive, the intermetallic compound Mg_2Si with blocky structure or in Chinese script shape can't effectively refine the grain and hinder dislocation movement, causing the decrease of alloy strength.

The elongation of as-cast Mg-9Li-3Al-xSi alloys keeps decreasing with the increase of Si content. It is because Mg_2Si intermetallic compound is mainly distributed in the interface of α phase and β phase, impeding the dislocation moving by its pinning effect. Hence the plasticity of alloy is reduced. With the further increase of Si content, Mg_2Si is formed with the blocky structure or Chinese script shape. The bulky Mg_2Si is apt to create a stress concentration, generating the cracks which are liable to spread along the boundary of Mg_2Si and α-Mg. The growth of Mg_2Si promotes the generating and spreading of the cracks, leading to the degradation of comprehensive mechanical property of alloys[19].

As shown in Fig.7, the fracture mechanism of as-cast Mg-9Li-3Al-xSi alloys is the typical composite rupture, in which some tearing ridges of dimple and cleavage rupture exist. In Fig.7a, the fracture of as-cast Mg-9Li-3Al alloy has many dimples which are large and deep with few tearing ridges. With the addition of Si, especially when the content of Si is 1%, the dimples become fewer and the diameter gets smaller while the number of tearing ridges increases. That makes the fracture of alloy possess the features of composite rupture of dimple rupture and cleavage rupture. The fracture appearance of as-cast Mg-9Li-3Al-xSi alloy is consistent with its mechanical property of mentioned above. These features precisely explain why the plasticity of alloy decreases.

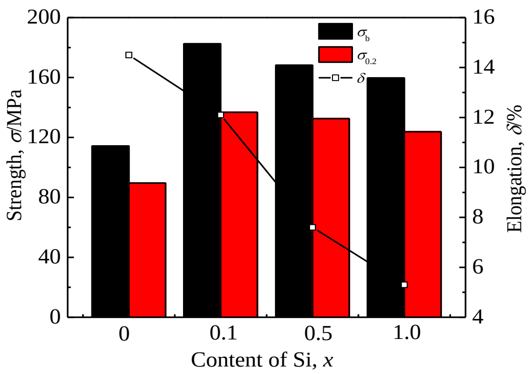

Fig.6 Mechanical properties of Mg-9Li-3Al-xSi alloys

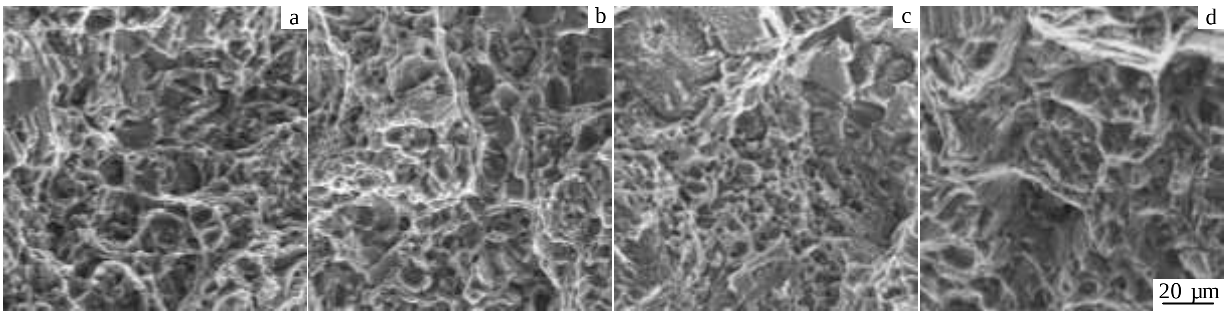

Fig.7 Fracture morphology of as-cast Mg-9Li-3Al-xSi alloys: (a) x=0, (b) x=0.1, (c) x=0.5, and (d) x=1.0

3 Conclusions

1) The addition of Si can refine α-Mg and form granular

Mg_2Si at the phase boundary. However, when the content of Si is excessive, the α-Mg gets bulky and blocky structure or Chinese script Mg_2Si is formed in the phase boundary.

2) Mg-9Li-3Al mainly consists of α-Mg, β-Li and $Mg_{17}Al_{12}$ phases. With the addition of Si, the main phases are α-Mg, β-Li and Mg_2Si phases. Moreover, the addition of Si can restrain the formation of $Mg_{17}Al_{12}$.

3) With the increase of Si content, the strength of Mg-9Li-3Al-*x*Si alloys increases first and then decreases, while the elongation decreases. When the content of Si is 0.1%, the alloy shows a favorable combination of ductility and strength with an ultimate tensile strength of 182.5 MPa, yield strength of 136.8 MPa, and an elongation of 12.1%. Compared with Mg-9Li-3Al alloy, the yield strength and tensile strength increase by 59.6% and 52.6%, respectively.

4) The fracture of alloy consists of tearing ridges and some dimples, which is the typical composite rupture of dimple rupture and cleavage rupture. With the increase of Si content, the dimples become fewer and smaller while the number of tearing ridges increases gradually.

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铸态Mg-Li-Al-*x*Si合金微观组织和力学性能

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摘　要：实验铸造了Mg-9Li-3Al-*x*Si（*x*=0, 0.1, 0.5, 1.0, 质量分数，%）合金并通过OM，SEM，XRD和力学性能测试对其进行了研究。结果表明：铸态Mg-9Li-3Al合金组织中主要由α-Mg、β-Li、$Mg_{17}Al_{12}$相组成。加入Si后，合金中出现了新相Mg_2Si，晶粒得到了明显细化，且Si能够抑制$Mg_{17}Al_{12}$的形成；当合金中的Si含量过高时，α-Mg相粗化，且会在相界处出现块状和汉字状的Mg_2Si相。合金的强度随着Si含量的增加呈现先增加后降低的趋势，合金的延伸率随着Si含量的增加呈现逐渐降低的趋势。当合金中Si含量为0.1%时，抗拉强度达到最大值182.5 MPa，延伸率为12.1%。

关键词：镁合金；显微组织；力学性能；硅元素

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