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# Influence of yttrium on microstructure and mechanical properties of as-cast Mg–5Li–3Al–2Zn alloy

Chongliang Cui, Libin Wu, Ruizhi Wu*, Jinghuai Zhang, Milin Zhang

*Key Laboratory of Superlight Materials & Surface Technology, Ministry of Education, Harbin Engineering University, Harbin 150001, China*

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ABSTRACT

The influence of Y on microstructure and mechanical properties of as-cast Mg–5Li–3Al–2Zn alloy was investigated. The results show that the phase compositions of Mg–5Li–3Al–2Zn consist of α-Mg and AlLi phases. Adding Y to the alloy results in the formation of $Al_2Y$ compound and facilitates grain refinement. The addition of 0.8 wt.% Y produces the smallest grain size. The tensile tests performed at room temperature show that the additions of Y can improve the mechanical properties of the alloy; the tensile strength and ductility reach peak values when the Y additions are 0.8 wt.% and 1.2 wt.%, respectively. The mechanisms of improvement are related to grain refinement and compound strengthening effects.

## 1. Introduction

Mg–Li alloys are well known as super-light alloys. As the lightest metallic materials, Mg–Li alloys not only have high specific strength and specific stiffness, but also have good damping and electromagnetic shielding performances. Mg–Li alloys are widely used, therefore, in the fields of weapons, aerospace, electronics, automotive and other industries [1–3].

According to the Mg–Li phase diagram, when Li content is lower than 5.7 wt.%, the microstructure of the alloy is single phase (α). The alloy with this structure has relatively high strength compared with other alloys containing higher Li content. Many research studies on this type of Mg–Li alloy have been carried out [4–7]; however, due to low strength, poor corrosion resistance, and poor thermal stability, Mg–Li binary alloy is difficult to use directly in industrial applications [8].

Therefore, adding other alloying elements to obtain the strengthening effects and improve the mechanical properties of the alloy has become a research priority [9].

Y is an excellent alloying element in Mg–Li based alloys. Adding only a small amount of Y can significantly improve the mechanical properties of the alloy [10]. We report on the effect of Y additions on microstructure and mechanical properties of as-cast Mg–Li–Al–Zn alloy.

## 2. Experimental procedures

The materials used in our experiments were pure magnesium (99.95 wt.%), pure lithium (99.90 wt.%), pure aluminum (99.90 wt.%), pure zinc (99.90 wt.%) and Mg–25.67 wt.% Y master alloy. Mg–5Li–3A1–2Zn–$x$Y ($x$ = 0, 0.4, 0.8, 1.2, 1.6, 2.0) alloys were prepared in a vacuum electromagnetic induction melting furnace under the ambient of argon gas. The metallographic specimens sectioned from the ingots were polished and etched with 3 vol.% natal to reveal the microstructure. The micrographs of the alloys were obtained using an optical microscope. The microstructure and microzone compositions were analyzed with SEM and EDS. The phase analyses were performed by XRD. The mechanical properties of the alloys were tested on a standard tensile tester with a speed of 1 mm $min^{-1}$. The geometrical dimension of the tensile specimen is shown in Fig. 1.

## 3. Results

### 3.1. Influence of Y on microstructure of alloys

Fig. 2 shows the micrograph of as-cast Mg–5Li–3Al–2Zn–1.6Y alloy. It can be obviously seen that an abundance of blocky eutectic structure is formed and distributed along the grain boundaries with discontinuous network morphology; a small quantity of granular particles still exists inside the grains.

To observe the change of grain size due to Y additions, the alloys were treated with solid solution. The addition of Y has a refining effect on the grain size (Fig. 3). In more detail, the best refining effect is obtained when Y content is 0.8 wt.%. Otherwise, many black spots occur in the alloys after solid solution; the high magnification images of the alloy are observed using SEM to further reveal the spots. From the SEM image of LAZ532 alloy (Fig. 4), almost all the spots are gas pores which possibly form during the solid solution treatment. However, from the image of LAZ532–0.4Y alloy (Fig. 5),

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* Corresponding author. Tel.: +86 451 82533026; fax: +86 451 82533026.
*E-mail address:* Ruizhiwu@yahoo.com (R. Wu).

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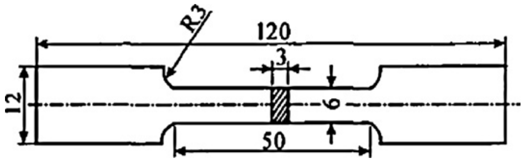


**Fig. 1.** Sketch of tensile test specimen and its gauge size (mm).

besides very few gas pores, many small particles, which are rich in Al and Y, are dispersed in the alloy.

### 3.2. Phase composition of alloys

XRD patterns of the alloy, with different additions of Y, show that the LAZ532 alloy is composed of α-Mg and AlLi phases (Fig. 6a). With the addition of Y, $Al_2Y$ peaks appear while AlLi peaks disappear gradually. Line scanning analysis for the polygonal compound in the alloy shows that Al and Y contents increase quickly in the location of polygonal compound (Fig. 7). EDS microanalysis (Fig. 8) indicates that the Al/Y ratio of this compound is about 2:1. From these results, we conclude that the polygonal compound distributing inside grains is $Al_2Y$.

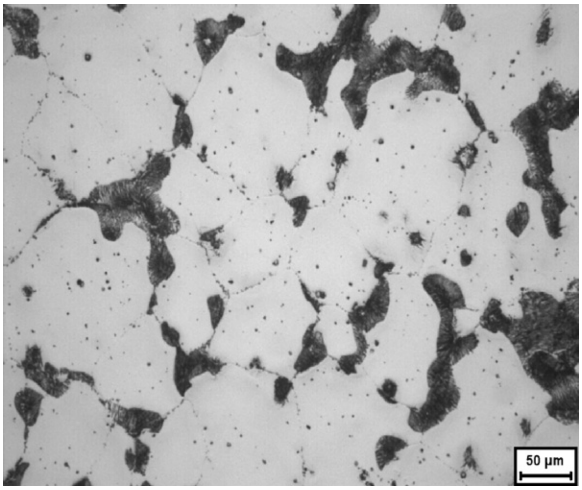


**Fig. 2.** Micrograph of Mg–5Li–3Al–2Zn–1.6Y alloy.

### 3.3. Effect of Y on mechanical properties

Fig. 9 shows the ultimate tensile strength ($\sigma_b$) and elongation to failure ($\delta$) of the alloy with different Y contents. The tensile

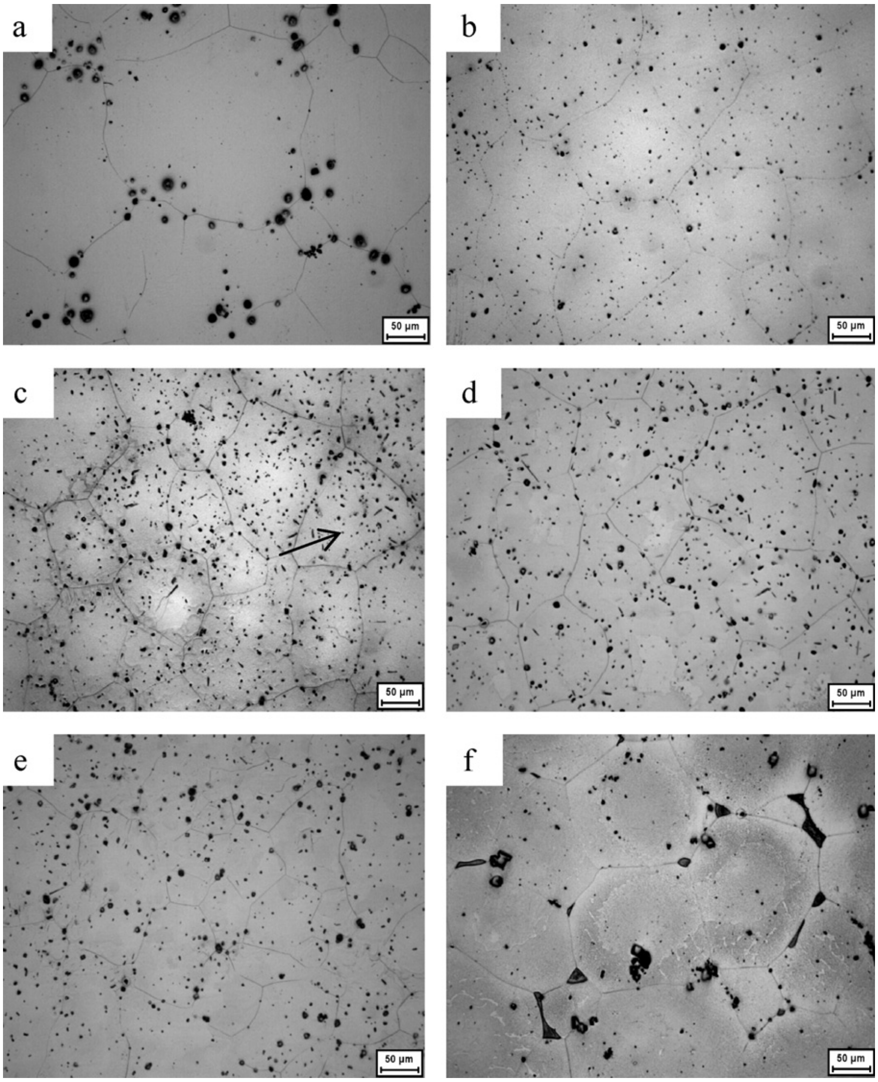


**Fig. 3.** The effect of Y content on grain size: (a) Mg–5Li–3Al–2Zn alloy, (b) Mg–5Li–3Al–2Zn–0.4Y alloy, (c) Mg–5Li–3Al–2Zn–0.8Y alloy, (d) Mg–5Li–3Al–2Zn–1.2Y alloy, (e) Mg–5Li–3Al–2Zn–1.6Y, (f) Mg–5Li–3Al–2Zn–2.0Y (solution treated at 350 °C for 6 h).

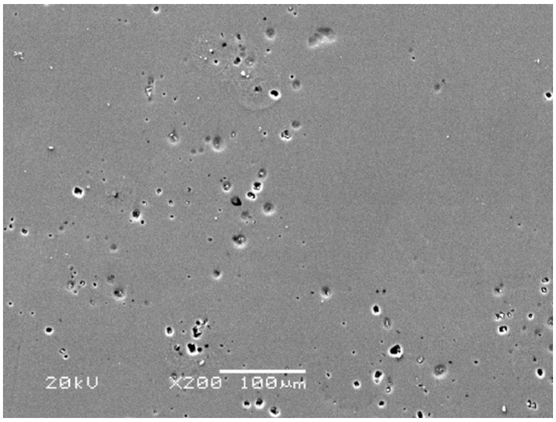


**Fig. 4.** SEM image of as-cast Mg–5Li–3Al–2Zn alloy.

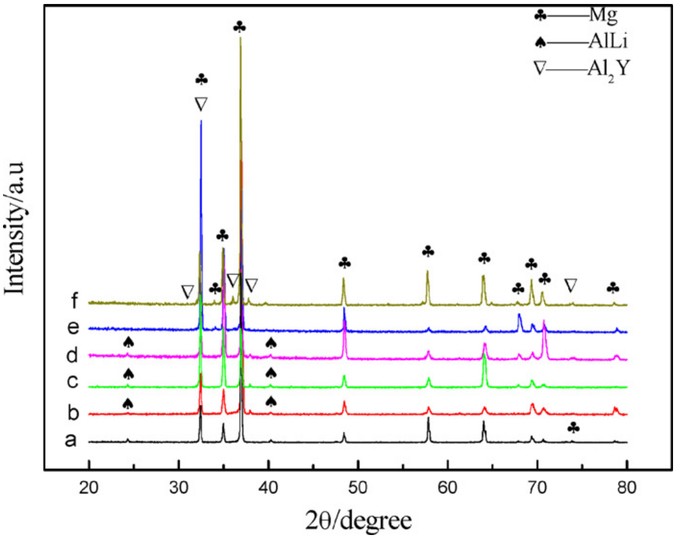


**Fig. 6.** XRD patterns of the alloys: (a–f) spectra with 0–2.0 wt.% Y additions, respectively.

strength and elongation both decrease to the lowest values when Y content is 0.4 wt.%. However, the tensile strength and elongation are improved significantly with Y addition up to 0.8 wt.% where tensile strength reaches a peak value and increases by 32.66% compared with that of the alloy without Y. Further increasing Y content results in the reduction of tensile strength, whereas elongation still improves and reaches a peak value which increases by 15.6% compared with that of alloy without Y, when Y content is 1.2 wt.% However, both tensile strength and elongation declined with 2.0 wt.% Y content. These results indicate that an appropriate addition of Y (about 1 wt.%) is effective for improving tensile strength and ductility of the LAZ532 alloy.

## 4. Discussion

The addition of Y in Mg–Li alloys reduces the solidus temperature of the alloy and shortens the nucleation time. The grain size of Mg–Li alloys containing Y can be refined [11]. In addition, Y can serve as a heterogeneous nucleating agent for α-Mg, which also facilitates grain size refinement. By optimizing the edge-to-edge model, Yang et al. [12] have obtained a stable phase relationship between α-Mg and α-Y, revealing that α-Y could serve as a grain refiner. Therefore, Y can produce an effect of grain refinement in Mg alloys.

The difficulty in forming compounds from elements can be mainly evaluated according to electronegativity difference [13]. From Table 1 the difference between Y and Al is largest. Although the electronegativity difference between Y and Zn is also large, considering Zn and Mg both belong to a hexagonal crystal structure, it is possible that all Zn atoms in alloys dissolve in α(Mg) phase and strengthen the matrix. Whether from phase analysis or atomic radius, there is no possible way to form compounds between Y and Li. Some Y atoms dissolve in α(Mg) phase, others form $Al_2Y$ compounds combining with Al. $A1_2Y$ has a face-centered cubic crystal structure with lattice constant $a = 0.786 \times 10^{-9}$ m. Its high melting point (1485 °C) causes it to be formed before α(Mg) solidification. Therefore, this $A1_2Y$ preferential phase hinders grain growth; it also provides the strengthening effect on the matrix.

The solid solution strengthening and grain refining effects are weak with small Y addition, and the formation of $Al_2Y$ phase also consumes Al atoms which dissolve in the matrix and contribute to the strengthening effect. These factors mentioned above are unfavorable for the mechanical properties of alloys. As a result, the improvement of mechanical properties of the alloy with 0.4 wt.% Y is not realistic. When Y content is 0.8 wt.%, the tensile strength and elongation are improved due to the strengthening of solid solution and refining of grain refinement. With further addition of Y, tensile strength and elongation start to decline. From optical micrographs of alloys, grain refinement is the main factor for improvement of strength and elongation. In addition, the relatively large solid solubility of Y causes a good reinforcement effect. However, excessive addition of Y coarsens grains, and $A1_2Y$ particles start to aggregate. On the other hand, the decrease of AlLi phase owing to Y addition also produces a negative effect on the strength of alloys. These are responsible for the decline of the mechanical properties of the alloys.

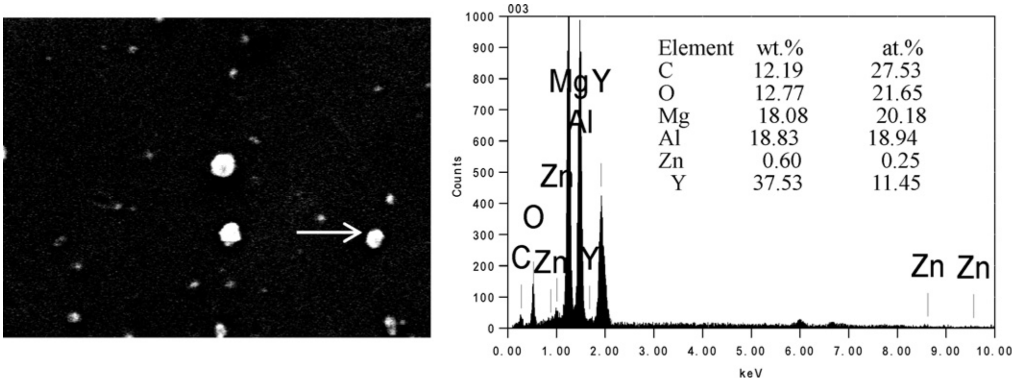


**Fig. 5.** EDS analysis of as-cast Mg–5Li–3Al–2Zn–0.4Y alloy after solid solution treatment.

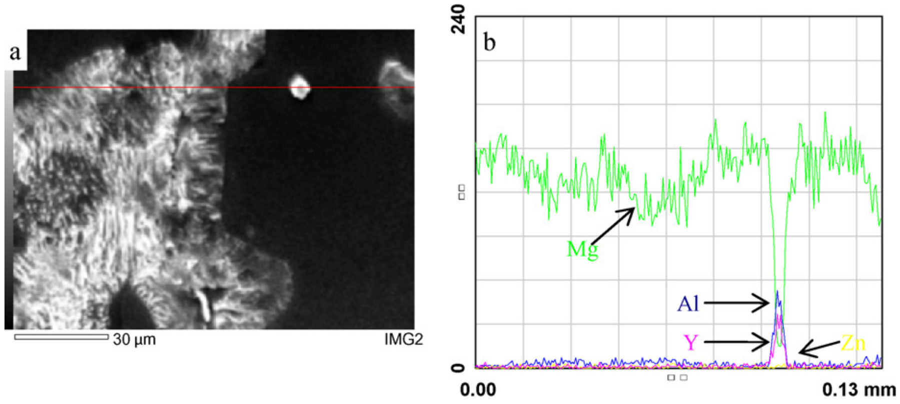
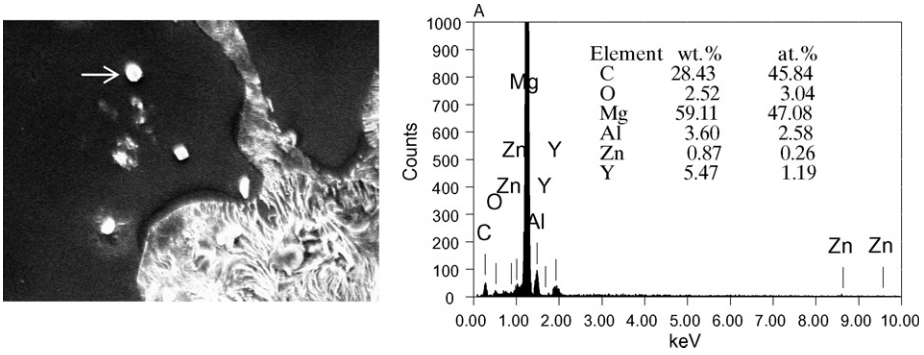


**Fig. 7.** EDS line scan showing the distribution of elements in Mg–5Li–3Al–2Zn–1.6Y specimen: (a) scan position and (b) distribution of elements.



| Element | wt.% | at.% |
|---|---|---|
| C | 28.43 | 45.84 |
| O | 2.52 | 3.04 |
| Mg | 59.11 | 47.08 |
| Al | 3.60 | 2.58 |
| Zn | 0.87 | 0.26 |
| Y | 5.47 | 1.19 |

**Fig. 8.** SEM image and EDS microanalysis of Mg–5Li–3Al–2Zn–1.6Y alloy.

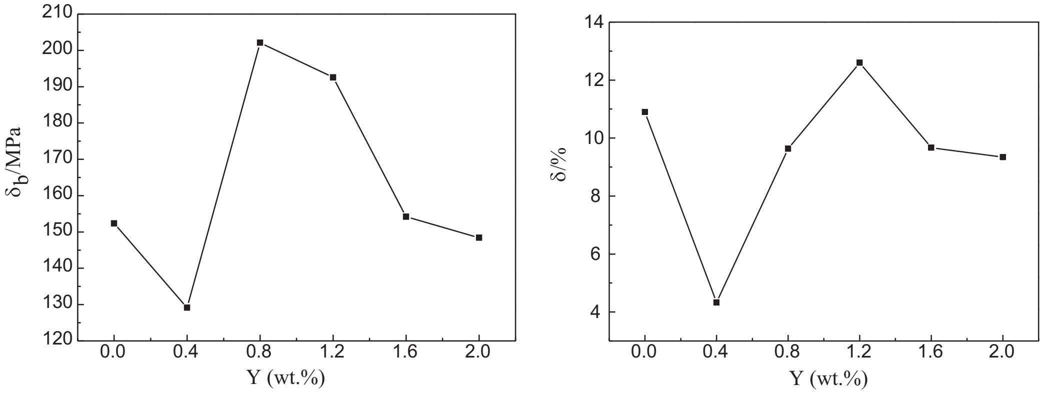


**Fig. 9.** Effect of different Y contents on mechanical properties of Mg–5Li–3Al–2Zn alloys.

**Table 1**
Atomic radii and electronegativity of elements in Mg–5Li–3Al–2Zn–*x*Y alloys.

| Element | Atomic radius (Å) | Radius difference compared with Y (%) | Electronegativity (Pauling scale) | Electronegativity difference compared with Y (%) |
|---|---|---|---|---|
| Mg | 1.60 | 12.08 | 1.31 | 7.37 |
| Li | 1.55 | 14.83 | 0.98 | 19.67 |
| Al | 1.43 | 21.42 | 1.61 | 31.96 |
| Zn | 1.33 | 26.92 | 1.60 | 31.14 |
| Y | 1.82 | 0 | 1.22 | 0 |

## 5. Conclusions

(1) When Y content is 0.8 wt.%, the grain size of the alloy is smallest and tensile strength reaches the highest value.
(2) With the addition of Y, $Al_2Y$ phase appears in the alloy, and decreases the precipitation of AlLi phase.
(3) When the Y content exceeds 0.8 wt.%, the tensile strength of alloys starts to decline. When Y content exceeds 1.2 wt.%, ductility begins to deteriorate.
(4) Adding an appropriate amount of Y (about 1 wt.%) in the Mg–5Li–3Al–2Zn alloy brings about strengthening of grain refinement and second phase strengthening.

## Acknowledgements

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