# EFFECT OF DOUBLE-AGING ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF RS / PM Al-Li ALLOY①

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## ABSTRACT

The effect of double-aging on the microstructure and mechanical properties of a RS / PM Al–Li alloy has been investigated. The results show that the ductility of the alloy can be greatly improved by the treatment of prior-aging at 170 ℃ for 4 h and second-step aging at 190 ℃ for 18 h after solid solutioning. The formation of a large amount of composite precipitates ($AlLi_3$ / $Al_3(Li,Zr)$) with suitable size, narrowing of $\delta'$ ($Al_3Li$) precipitate-free zone (PFZ) at grain boundaries and more dispersive precipitation of S′ ($Al_2CuMg$) phases along substructures are responsible for the improvement of the ductility of the studied alloy.

**Key words:** Al–Li alloy rapid solidification double-aging

## 1 INTRODUCTION

It is well known that Al–Li based alloys have low plasticity corresponding to higher strength. The plasticity and toughness of Al–Li as-cast alloys have been greatly improved by prior cold deformation–step aging treatment after solid solutioning[1–3]. But this kind of treatment is not suitable for the Al–Li alloys prepared using rapid solidification-powders metallurgy processing(RS / PM) because most RS / PM Al–Li alloy products are in the form of forging and extrudates. In order to improve the plasticity and toughness of these kind of alloys, some work has been done by kim *et al*[4]. They found double-aging treatment benefited the plasticity and toughness of the alloys and suggested that the improvement in ductility was correlated to the formation of more composite precipitates ($Al_3Li$ / $Al_3(Li,Zr)$). The purpose of this study was to investigate the effect of double-aging on the microstructure and mechanical properties of one kind of Al–Li–Cu–Mg–Zr alloy prepared using multistep rapid solidification (MS–RS) processing, and to find the optimum microstructure mode and double-aging processing corresponding to the superior plasticity of this alloy.

## 2 MATERIALS AND EXPERIMENTAL PROCEDURE

The studied alloy was prepared from the foil shape powders obtained using MS–RS technique. The RS powders were cold compacted, vacuum degassed and pressed at 470 ℃, then extruded into bars at 400 ℃. The composition of the alloy is as follows (wt. –%):

| Li | Cu | Mg | Zr | Fe | Si | Al |
|---|---|---|---|---|---|---|
| 2.52 | 1.60 | 1.22 | 0.20 | 0.12 | 0.80 | bal. |

The extrudates were solution treated at 525 ℃ for 40 min in an argon atmosphere, and cold water quenched. In order to investigate the effect of aging processing on the

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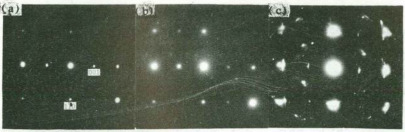


**Fig. 6 The change of [110] zone SAED pattern of the $B_2$ structure at 353 K(a); 300 K(b); 183 K(c)**

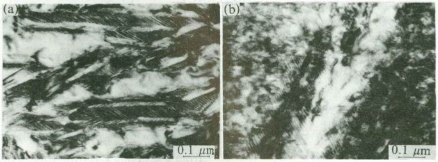


**Fig. 7 Micrograph of the martensites at 183 K**

(a) needle-like (b) plate-like martensites

(2) The lattice of the *R* phase may be referred to a hexagonal unit cell of a = 0.736 nm, c = 0.521 nm, and the relative orientation of the $B_2$ and *R* phases are

$$(1\bar{1}0)_{B_2} \; // \; (10\bar{1}0)_R, [111]_{B_2} \; // \; [0001]_R$$

(3) The *R* transformation is a first-order transformation and the *R* phase is not a premartensitic phase, which is associated with the two-way shape memory effect.

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same total aging time, double-aging can produce more S′ phases and a larger amount of $Al_3Li$ / $Al_3(Li, Zr)$ composite precipitates in which the core is $Al_3(Li,Zr)$ and is surrounded by $\delta'$ ($Al_3Li$) phase[5,6]. In addition, the width of $\delta'$ precipitate-free zone (PFZ) at grain boundaries in double-aged alloys is narrower than in single-aged alloys. Actually, a great number of composite precipitates had formed during prior-aging at 170 ℃ for 4 h (Fig. 3a), but those particles were not easily observed because of their small size. For convenient comparison, some characteristics for microstructures of the alloy under different treatment conditions are summarized in Table 2.

## 4 DISCUSSION

### 4.1 *The Effect of Double-aging on the Formation of Composite Precipitates* ($Al_3Li$ / $Al_3(Li, Zr)$) *and the Width of* PFZ

**Table 2 Comparison of the microstructure characteristics of the alloys after different treatment**

| Aging | Average $\delta'$ Size / nm | Half PFZ Width / nm | Amount of Composite Precipitates | Amount of S′ Phases |
|---|---|---|---|---|
| 190 ℃, 6 h | 15 | 47 | minor | a little |
| 190 ℃, 20 h | 20 | 84 | minor | minor |
| 170 ℃ / 4 h+ 190 ℃ / 2 h | 14 | 38 | large amount | major |
| 170 ℃ / 4 h+ 190 ℃ / 18 h | 19 | 65 | large amount | large amount |
| 170 ℃ / 4 h+ 190 ℃ / 30 h | 23 | 91 | large amount | large amount |

In the literature most mechanisms for the formation of the composite precipitates have suggested that $\delta'$ ($Al_3Li$) phases inhomogeneously precipitate along $Al_3Zr$ dispersoids. Because of the similarity in structure of $Al_3Zr$ and $Al_3Li$, these pre-existing dispersoids should be the most favorable nucleation sites for the precipitation of $\delta'$ phase. It seems the quantity and distribution of composite precipitates depend on that of $Al_3Zr$ particles. However, the results from Fig. 2b and Fig. 4c show that the amount of composite precipitates in aged alloys was more than that in as-quenched alloys. Furthermore, the formation of composite precipitates also depended on the aging temperature. All of this indicates that $Al_3Zr$ dispersoids are not the sole nucleation sites for the formation of composite precipitates. Kim *et al*[4] suggested that diffusion of Li and clustered Zr plays an important role during the formation of composite precipitates at certain aging temperatures. At present, the details of the mechanism is not clear but may be attributed to the existence of Zr clusters in solution treated alloy. When the alloy is aged at a suitable temperature (such as 170 ℃), this kind of cluster interacts with Li atoms to form $Al_3(Li,Zr)$-type precursors with increasing aging time and / or temperature composite $Al_3Li$ / $Al_3(Li,Zr)$ precipitated and could be observed under TEM. The present study showed that when the alloy experienced 170 ℃, 4 h prior-aging followed by second-step aging at 190 ℃ the amount of composite precipitates obviously increased. Although the results of microstructure observation are confirmed, a more precise explanation of this phenomenon is hard to be given yet due to lack of relevant thermodynamic data, and more detailed studies need to be done in the future.

In addition, the authors also suggested that composite precipitates $Al_3Li$ / $Al_3$ (Li,Zr) be more stable than those $\delta'$ particles which directly precipitated from the matrix. During the second-step aging for double-aged alloys, the widening of PFZ at grain boundaries was difficult due to the formation of many stable composite precipitates at the prior-aging stage. But for single-aged alloys at 190 ℃, with increasing aging time, the substable $\delta'$ particles along grain boundaries were easy to dissolve, and equilibrium phases occurred, finally leading to a widening of PFZ at grain boundaries terribly.

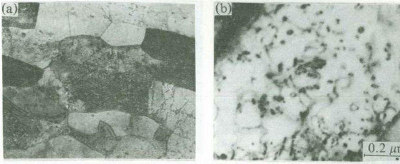


**Fig. 2 Microstructure of solution treated alloy**

(a)—grains and substructures; (b)—$Al_3Zr$ particles and dislocation loops

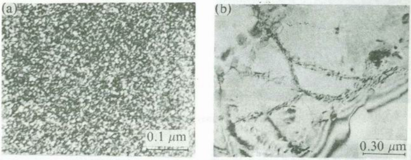


**Fig. 3 Precipitate characteristics of the alloy aged at 170 ℃ for 4 h**

(a)—DF image of precipitates in the matrix; (b)—$S'$ ($Al_2CuMg$) phases on subgrain boundaries

### 4. 2 · *The Effect of Double-aging on the Precipitation of* $S'$ ($Al_2CuMg$) *Phases*

In RS / PM Al–Li alloys, apart from finer grains, there are a large amount of substructures, such as subgrain boundaries, dislocations, etc., which are favorable sites for the precipitation of $S'$ phases, so more $S'$ phases can be expected to occur without thermo-mechanical treatment processing. However, the precipitation of $S'$ phases has a incubation period, and the incubation time, depends on aging processing. With the increasing of aging time, $\delta'$ particles formed and coarsened, and the vacancies bounded by Li atoms were released. When these free vacancies moved to the defects (such as surface, grain boundaries and dislocations), the diffusion of Cu and Mg atoms should be accelerated by the interaction between the free vacancies and Cu and Mg atoms, and led to rich content of Cu and Mg near the defects, which promoted the precipitation of $S'$ phases[7]. The adapting of double aging the diffusion rate of free vacancies at the prior-aging stage became slow, i. e., "the ability" of Cu and Mg atoms to be carried by free vacancies increased, thereby increasing the driving force for $S'$ precipitation. Therefore, double-aging treatment is beneficial to $S'$ phases precipitation.

### 4. 3 *The Effect of Double-aging on the Plasticity of the Alloy*

In the aged Al–Li alloys, the particle size

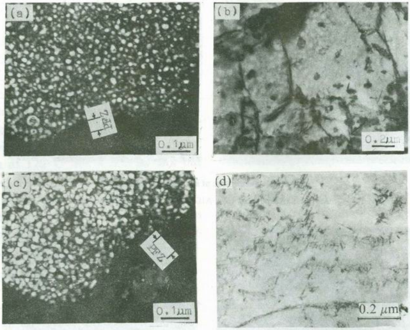


**Fig. 4 Precipitate characteristics of the alloy aged at 190 ℃ ((a), (b)—6 h; (c), (d)—20 h)**

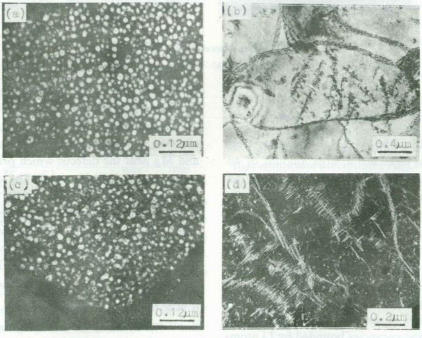


**Fig. 5 Microstructure of the alloy with different second-step aging time at 190 ℃ after prior-aged at 170 ℃ for 4 h**

(a), (b)—2 h; (c), (d)—18 h;

of $\delta'$ phase depends on the behaviour of the interaction between the dislocation and $\delta'$ particles during the deformation of the alloys[8]. For single over-aged alloys, coarse $\delta'$ particles (average diameter was greater than 15 nm) made the dislocations bypass them, and a great amount of S′ phases dispersively precipitated. These factors weakened the coplane slip and led to more homogeneous deformation. However, more equilibrium phases occurred and PFZ greatly developed at grain boundaries. At this condition, the deformation could preferentially occur within the soft PFZ and strain localization led to microvoids around equilibrium phases, finally resulting in low plasticity fracture along PFZ. The results comprehensively acted by the two kinds of contradictory factors mentioned above made the plasticity of single over-aged alloy rise slightly again, but it was still low. Table 2 shows that suitable double-aging (such as 170 ℃, 4 h+190 ℃, 18 h) not only kept $\delta'$ particle size the same as that of single-aged (190 ℃, 20 h) alloy, but also greatly increased the amount of S′ precipitates and narrowed the width of PFZ at grain boundaries. In patrticular, double-aging promoted the formation of a large amount of composite particles $Al_3Li$ / $Al_3$ (Li,Zr), which are hard to be sheared by dislocations due to their hard core and higher boundary energies, which also weakened the coplane slip. Combining all above, it is generalized that double-aging can promote the formation of beneficial microstructures and prohibit the development of detrimental microstructures, leading to the improvement of the ductility of the alloy.

## 5 CONCLUSIONS

(1) Double-aging treatment can significantly improve the plasticity of RS / PM Al–Li alloy. In the present work the optimum double-aging processing is prior-aging at 170 ℃ for 4 h followed by second-step aging at 190 ℃ for 18 h;

(2) A large amount of composite precipitates ($Al_3Li$ / $Al_3$(Li,Zr)) with suitable size, narrowing of $\delta'$ precipitate-free zone(PFZ) at grain boundaries and more dispersive precipitation of S′ ($Al_2CuMg$) phases along substructures are mainly responsible for the improvement of the plasticity of the alloy.

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