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# Aging of Al-Li Alloys Having Composite Particles of Hardening Phases

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## Abstract

Characteristic features of heat treatment of aluminium-lithium alloys are connected mainly with a presence of the general hardening phase δ' ($Al_3Li$) both independently and as a shell on θ', θ'', $Al_3Zr$ and $Al_3Sc$ phases of composite two-phase particles. Influence of the multi-step artificial ageing of Al-Li-Cu, Al-Li-Mg-Cu and Al-Li-Mg alloys on phase composition, precipitates morphology (particle size and distance between them), presence and width of precipitated free zones along boundaries is studied. Usage of multi-step ageing regimes allows to increase a fracture toughness, corrosion resistance and thermal stability in comparison with one-step ageing for Al-Li alloys.

## 1. Introduction

Multi-component commercial Al-Li alloys are characterized by a high degree of alloying (9-14 at.%), a considerable heterogeneity and complexity of phase transformations both under the manufacture of semi-products and their final heat treatment, that influences considerably on the alloy properties, especially on characteristic of crack resistance, fracture toughness and corrosion resistance.

Multi-step ageing is the most effective method to influence the structure and properties of multi-phase ageing alloys [1-4]. For the first time the step ageing has been developed for Al-Zn-Mg-Cu alloys. A considerable influence of preliminary zone ageing on the following phase ageing was established for them.

In the present work the efficiency of multi-step ageing used for Al-Li alloys has been determined.

## 2. Results and Discussion

Studies of the morphology of oversaturated solid solution (OSS) decomposition of Al-Li-Cu (1451, 1461), Al-Li-Mg-Cu (1430) and Al-Li-Mg (1424) alloys has been carried out under ageing in a wide time-temperature region on 2,5 mm sheets thickness by TEM, DSC, X-ray –structural analysis and resistometry.

During heat treatment of Al-Li alloys well – known phases θ′′, θ′, θ ($Al_2Cu$) and S′′, S′, S($Al_2CuMg$) for Al-Cu and Al-Cu-Mg alloys, a series of the new δ′($Al_3Li$), $T_1$($Al_2CuLi$), $T_2$($Al_6CuLi_3$), $S_1$ ($Al_2MgLi$), $Al_3Zr$, $Al_3Sc$ arises at the same time.

Multi-stage decomposition of OSS of Al-Li alloys takes place with the formation of different phases in the different time- temperature regions (Table 1).

Table 1: Scheme of Al-Li alloys OSS decomposition.

| Alloying | Al-Mg-Li | Al-Cu-Li | Al-Mg-Li-Cu |
|---|---|---|---|
| Decomposition $\alpha$-solid solution | $\rightarrow \delta'$<br>$\alpha$<br>$\rightarrow S_1$ | $\rightarrow \delta'$<br>$\alpha \rightarrow GP \rightarrow \theta'' \rightarrow \theta'$<br>$\rightarrow T_1$ | $\rightarrow \delta'$<br>$\alpha \rightarrow S_1$<br>$\rightarrow GPB \rightarrow S'' \rightarrow S'$ |

Two mechanisms of formation of hardening phases take place: 1- a primary precipitate is a nucleus of each new type precipitate and 2- an independent nucleation of a new type precipitate in the matrix, in particular, as a consequence of total or partial decomposition of the primary precipitates. There are time-temperature boundaries for a phase region. $T_{min}$, below which GP-zones do not reach a critical size for transformation in the new type of precipitate at higher ageing temperature and $T_{GP}$, above which, GP-zones either become the nuclei of the metastable phases or dissolve and the new type precipitates form from solid solution.

The general hardening metastable $\delta'(Al_3Li)$-phase is isomorphic to the matrix and ordered $L1_2$ type, it nucleates homogeneously. Moreover for multi-phase alloys this phase nucleates on inter-phase boundary of matrix and other phase, forming composite particles. Composite particles of two types with a shell of the metastable $\delta'$-phase are founded (Figure1).

The first type particles are observed in Al-Li alloys, alloyed with Zr and Sc, and consist of two isomorphic phases ordered by type $L1_2$. The kernel is $Al_3X$-phase, where X can be Zr, Sc or Zr+Sc. The second type particles are formed in Al-Cu-Li alloys. The kernels of these composite particles are the non-isomorphic tetragonal $\theta''$and $\theta'$-phases.

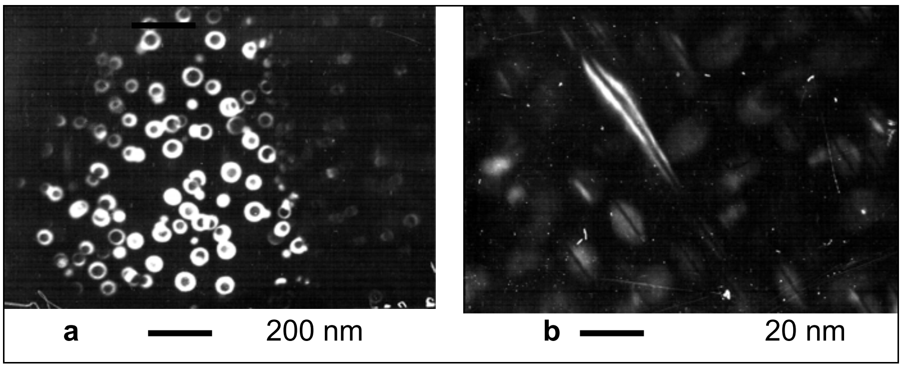


Figure 1: Composite particles of $Al_3(Zr,Sc) / \delta'$ (a) and $\theta'/ \delta'$ (b) Dark field image, (110) $\delta'$ reflection [5].

At the development of multi-step ageing a choice of time-temperature parameters is realized with an usage of diagram of phase transformation under ageing (DPTA), which have been plotted in consequence of structural investigation and definition the time-temperature boundaries of existence of different phases (Figure 2).

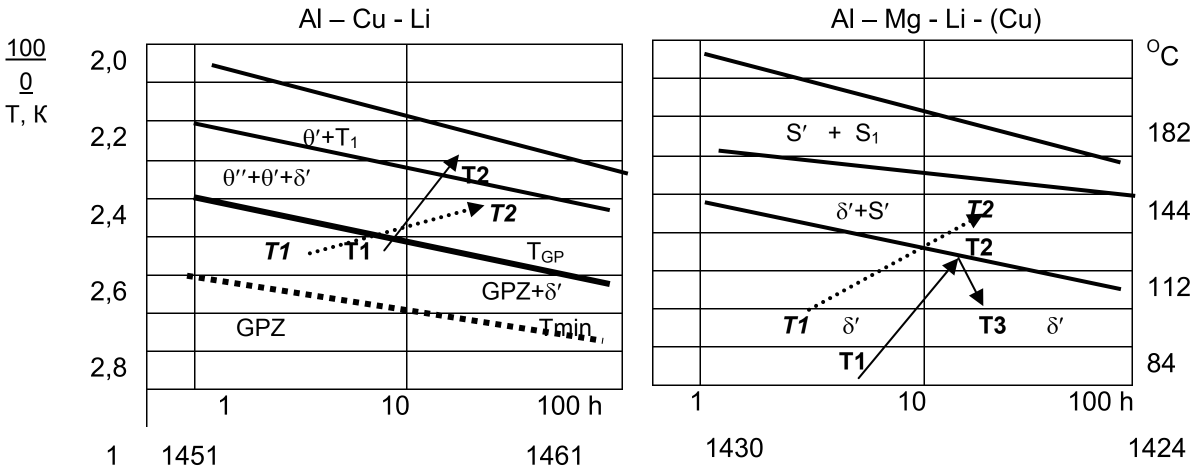


Figure 2: Al-Li alloys DPTA and step ageing schemes.

A temperature of the first step ageing for Al-Cu-Li alloys is chosen between $T_{min}$ and $T_{GP}$. At the first step of ageing (120-135$^0$C) the maximum quantity of composite particles of $\theta''/\delta'$ phase is formed, capable to a growth at higher temperatures (145-165$^0$C) [5].

The density of heterogeneously nucleated $\theta'$ and $T_1$ precipitates is relatively little. The high density of $\theta''/\delta'$ particles slows down both a growth of $\theta'$-phase and further $T_1$ precipitation at the second ageing step.

The 2-step ageing, in comparison with 1-step ageing, ensures an intensive precipitation of finer $\theta''/\delta'$ and $T_1$-phases in the grain body and decrease the quantity, size of $T_1$ precipitates and PFZ width (Table 2, Figure. 3).

Table 2: Influence of ageing regime on Al-Li alloys structure characteristics

| Alloy | Characteristic | | | Ageing 1-step | Ageing 2-step |
|---|---|---|---|---|---|
| 1451 Al-Cu-Li | Size of precipitate, nm | | $\theta''/\delta'$ | 30 | 16 |
| | | | $\theta'$ | 85 | 50 |
| | | | $T_1$ | 70 | absent |
| 1461 Al-Cu-Li | Size of precipitate, nm | | $\theta''/\delta'$ | 10 ($\delta'$) | 5 ($\delta'$) |
| | | | $\theta'$ | 60 – 145 | 20 – 40 |
| | | | $T_1$ | 60 – 166 | 20 – 80 |
| | PFZ width, nm | | | 70 - 145 | 40 – 80 |
| 1430 Al-Mg-Li-Cu | Size of precipitate, nm | Grain body | $\delta'$ | 10 | 4,7 |
| | | Grain boundary | $S_1$ | 6 - 200 | absent |
| | | | $S'$ | 4 - 40 | 1 – 4 |
| | PFZ width, nm | | | 60- 80 | absent |

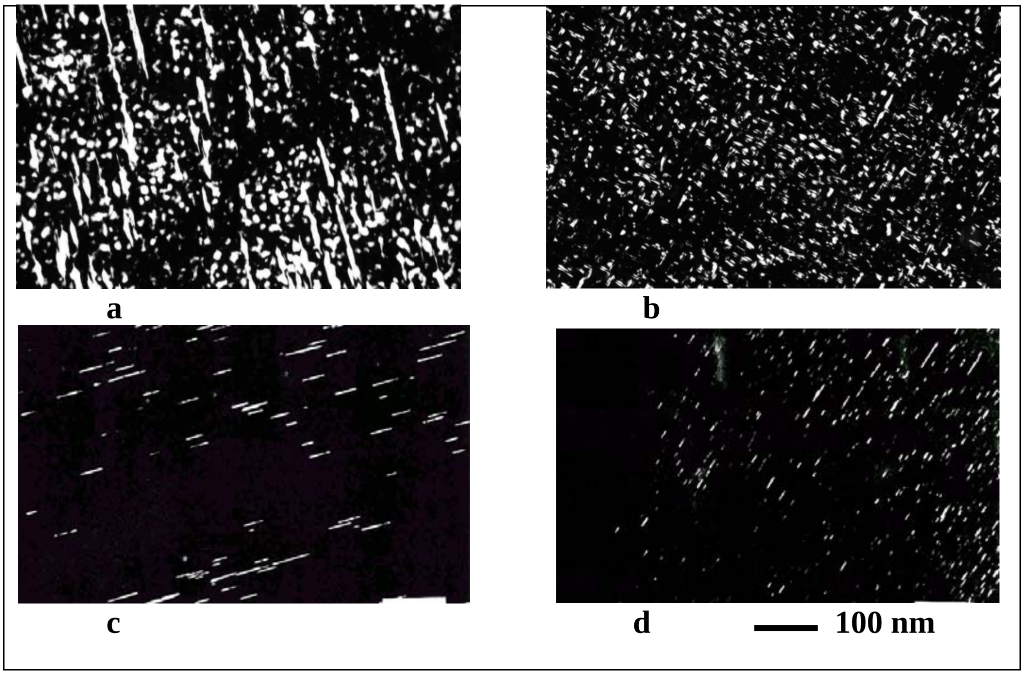


Figure 3: Precipitates of $\delta'$, $\theta''$, $\theta'$ (a, b) and $T_1$ (c, d) in 1461 alloy: a, c - 1-step ageing, dark field image, (001) $\delta'$ reflection;. b, d - 2-step ageing, dark field image, $T_1$ reflection.

Multy-step ageing is effective also for 1430 Al-Li-Mg-Cu and 1424 Al-Li-Mg alloys, which have practically a single strengthening $\delta'$-phase. At the ageing temperature of 140°C and higher, for 1430 alloy S′($Al_2CuMg$) strengthening phase is formed on the dislocations, introduced by straightening, and on the grain boundaries. Moreover, $S_1$($Al_2MgLi$)-phase precipitates on the grain boundaries at ageing temperature higher, than 150°C. The growth of these particles results in the forming the PFZ, that results in a decrease of fracture toughness and corrosion resistance. At the ageing temperature of 100°C a sufficiently high volume fraction (5-6%) of fine $\delta'$- phase precipitates is achieved during the first 3-5 hours [6]. At the second step of ageing at 140°C this volume fraction increases up to 8,5-9,0% mainly due to the growth of precipitate size. This 2-step ageing removes the continuous $S_1$-phase precipitates on the grain boundaries and forming the PFZ (Figure. 4,Table 2).

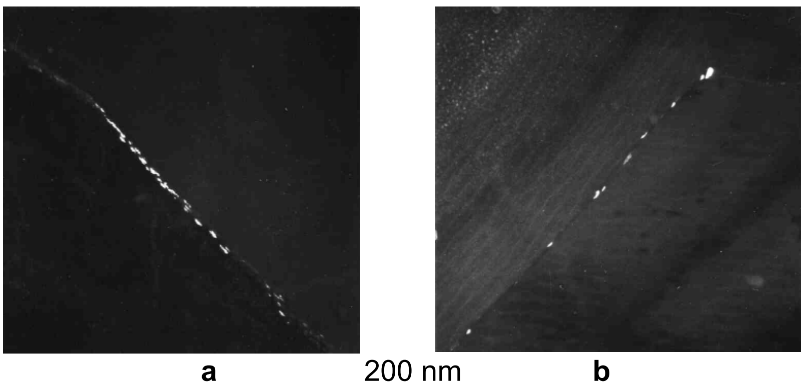


Figure 4: Precipitates of S1 in 1430 alloy after 1-step (a) and 2-step ageing (b)

The usage of 2-step ageing for 1451,1461 and 1430 alloys results in an increase of fracture toughness, crack and corrosion resistance, saving the level of strength characteristics as compared with 1-step ageing (Table 3).

Table 3: Influence of ageing regime on Al-Li alloys properties.

| Alloy | Characteristic | Ageing | |
|---|---|---|---|
| | | 1-step | 2-step |
| 1451 Al-Cu-Li | UTS ,MPa | 530 | 525 |
| | YS , MPa | 480 | 470 |
| | El , % | 8 | 10 |
| | $K_{c0}$, MPa√m (B=140mm) | 60 | 74 |
| | FCPR, da/dn, mm/kcycle, ΔK=31 MPa√m | 4 | 2,5 |
| | LCF, kcycle, $\sigma_{max}$=157 MPa, $K_t$=2,6 | 130 | 170 |
| | Exfoliation corrosion | EB | EA |
| 1430 Al-Mg-Li-Cu | UTS ,MPa | 470 | 465 |
| | YS , MPa | 375 | 375 |
| | El , % | 11 | 14 |
| | $K_{C0}$, MPa√m (B=140mm) | 60 | 75 |
| | FCPR, da/dn, mm/kcycle, ΔK=31 MPa√m | 2,2 | 1,2 |
| | Exfoliation corrosion | EB | EA |

Low temperature ageing of 1424 Al-Li-Mg alloy at 115-125 $^{O}$C ensures the best combination of mechanical and corrosion properties. However, in this case the supersaturation of solid solution by Li is retained. By this reason an additional precipitation of fine δ′- phase can take place during long-term low temperature exposure, leading to additional strengthening and decrease of fracture toughness by 20-25% [7, 8].

The use of 3-step ageing in the temperature range of 85-120$^{o}$C allows the following: owing to the low temperature (T1) a fine dispersion of δ′-phase precipitate in the first step, the second step (T2>T1) provides sufficient volume of it and the third step (T3<T2) leads to additional precipitation ly of δ′-phase that decreases the supersaturation of solid solution. Air quenching and 3-step ageing ensures a thermal stability of 1424 alloy properties after exposure for up to 3000 hrs [8].

## 3. Conclusion

1. Effect of multi-step ageing of Al-Li alloys is in that it influences decomposition of the solid solution decomposition at the first step on morphology of precipitates at the following steps. It results in a decrease of size and increase in the volume fraction of strengthening phases. The uniform distribution of precipitates also eliminates formation of non-desirable phases or provides a discreteness to stable phase precipitates along the grain boundary and a decrease of the width of precipitates free zone along the boundary (PFZ).
2. Usage of multi-step ageing regimes allows to increase fracture toughness, corrosion resistance and thermal stability in comparison with the one-step ageing for Al-Li alloys.

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