Effect of lithium on the aging characteristics and microstructure of Al-4Mg-1.5Cu-0.4Ag alloys[1]

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Small additions of silver can stimulate enhanced age hardening in certain Al-Cu-Mg alloys, and this effect is evident for a wide range of compositions selected in the $(\alpha + \theta)$, $(\alpha + \mathrm{S})$ and $(\alpha + \mathrm{S} + \mathrm{T})$ phase fields of the ternary phase diagram [1–4]. The addition of Ag to Al-Cu-Mg alloys with high Cu:Mg ratios stimulates the formation of an hexagonal-shaped precipitate phase, designated Ω, which occurs on matrix {111} planes. The effect of Ag is to increase the rate of hardening, raising the plateau and peak hardnesses while also decreasing the duration of the hardness plateau and time taken to peak hardness in the alloy in the $\alpha + \mathrm{S}$ phase field [5]. A MBED (micro beam electron diffraction) [6] study by Chopra *et al.*, has shown that a {111} phase, now designated X′, forms in the Al-2.5 wt%Cu-1.5 wt%Mg-0.5 wt%Ag alloy, possessing an hexagonal structure and oriented with $(0001)_{X'} /\!/ (111)_{\alpha}$. As with Al-Cu-Mg alloys in the $\alpha + \mathrm{S} + \mathrm{T}$ phase field, the addition of 0.5 wt%Ag to the alloy Al-1.5 wt%Cu-4.0 wt%Mg promotes the formation of a new phase, designated Z. A CBED investigation indicated that it has a fcc structure, with lattice parameter $a = 1.999$ nm [7], and an atom probe analysis show at the composition in the range Mg: 0.2–0.25, Cu: 0.20,Al: 0.5–0.6,and Ag enriched in the precipitate to levels as high as 5 at% [8]. Since an abnormal age hardening was observed in Al-4Cu-0.3Mg alloys containing silver and lithium by Polmear and Chester [9], which was attributed to the fine dispersions of the three intermediate precipitates Ω, θ' and S′, a new family of Al-Li alloys, Wedalite 049, has been developed by Pickens and his co-workers [10]. But up to now most of the investigations have concentrated on the Al-Cu-Mg alloys containing silver and lithium with high and medium Cu:Mg ratio, little work has been done in the low Cu:Mg ratio Al-Cu-Mg alloys.

The purpose of this letter is to report the effect of Li on the aging characteristics and microstructures of Al-Cu-Mg-Ag alloys with low Cu:Mg ratio.

The alloys were prepared by melting and casting under argon atmosphere, and their compositions are listed in Table I. The ingots were homogenized, scalped, then hot rolled and finally fabricated to 2 mm sheets by cold rolling. The specimens were solution treated and quenched into cold water, then aged at 170 °C. The age hardening response of the experimental alloys was monitored by micro hardness testing (Shimadzu) using a 200 g load. Foils for TEM were electropolished using a 33% nitric acid –67% methanol solution at around −35 °C. Examination for TEM was carried out with a Philips CM12 electron microscope with an accelerating voltage of 120 KV.

The age hardening curves at 170 °C for the A and B are given in Fig. 1. It can be seen that the form of the ageing curves of the two alloys is very similar, and only one ageing peak was observed during the whole ageing process at 170 °C. However, compared with the Li-free alloy A, significant increase in hardness is observed in the Li-containing alloy B, while the time taken to peak hardness is reduced. Investigations carried out earlier [2, 11] have shown that Ag additions have been effective in enhancing age hardening response in Al-4Mg-1.5Cu alloys. The present work indicates that the age hardening response can be further enhanced significantly

TABLE I The normal compositions of the studied alloys (wt%)

Alloys	Mg	Cu	Li	Ag	Zr	Al
A	4.0	1.5	0	0.4	0.12	Bal.
B	4.0	1.5	2.0	0.4	0.12	Bal.

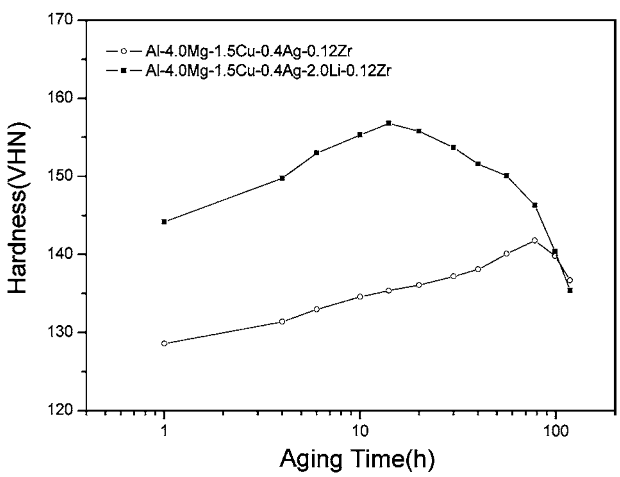

Figure 1 Age hardening response at 170 °C.

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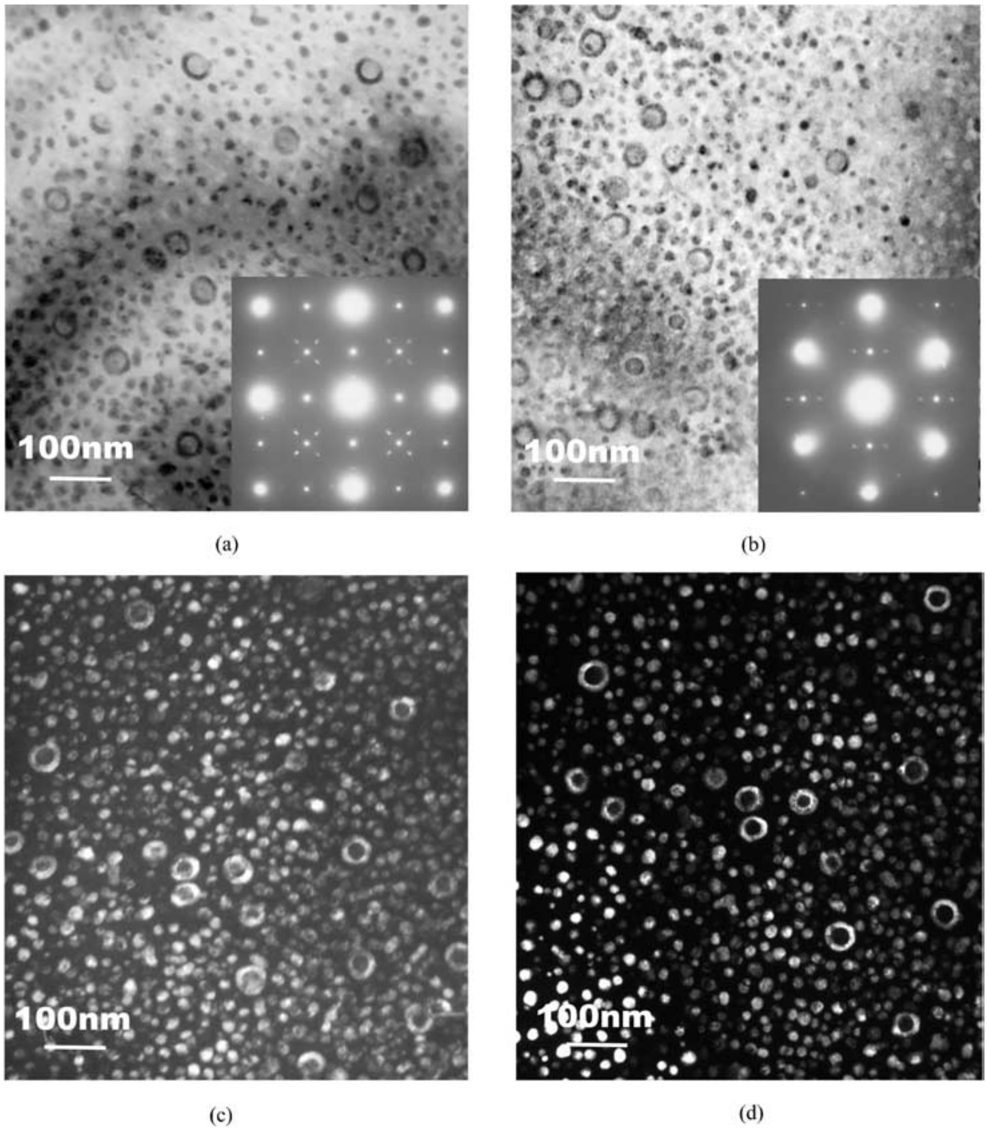

Figure 2 Transmission electron micrographs of the Al-4Mg-1.5Cu-0.4Ag-2.0Li-0.12Zr alloys aged at 170 °C for 16 h: (a) $\langle 001\rangle_\alpha$ BF image and corresponding SAED pattern, (b) $\langle 011\rangle_\alpha$ BF image and corresponding SAED pattern, (c) $\langle 001\rangle_\alpha$ DF image and (d) $\langle 011\rangle_\alpha$ DF image.

by the addition of Li in the Al-4.0Mg-1.5Cu-0.4Ag alloys.

Transmission electron micrographs of the peak aged microstructure for the alloy B during aging at 170 °C were recorded close to the $\langle 100\rangle_\alpha$ and $\langle 110\rangle_\alpha$ zone axes and examples are provided in Fig. 2. From the bright-field (BF), dark-field (DF) images and corresponding SAED patterns, it can be seen that the microstructure is dominated by $\delta'(Al_3Li)$ and spherical compound particles in the alloy B aged for 16 h. Additionally, there is Z phase precipitated in this alloy, since characteristic reflections near 1/3 and 2/3 **g** {220} are visible in the SAED pattern [7].

In order to study the spherical compound particles, MBED and EDXS were conducted on the sample. The analysis results are present in Fig. 3. MBED results show that the orientation of the compound particle is $(001)_\alpha /\!/ (001)_{\text{particle}}$, $[010]_\alpha /\!/ [010]_{\text{particle}}$. EDXS analysis shows that there appears to be a significant amount of Zr in the inner region of the compound particles, yet none in the outer shell. It is concluded that the outer shell probably consists of δ' precipitate similar to that formed in the matrix. Judging from the present EDXS and MBED results, the spherical compound particles precipitated in the Li-containing alloy B are Al_3Zr/Al_3Li particles. When the above data are considered together, the significant increase of age hardness may attribute to the fine dispersion of δ', Z phase and spherical Al_3Zr/Al_3Li compound particles in the alloy B.

In summary, the addition of lithium can greatly enhance the age hardening response of the Al-4.0Mg-1.5Cu-0.4Ag-0.12Zr alloy. The significant increase of age hardness is attributed to the fine dispersion of δ', Z phase and spherical Al_3Zr/Al_3Li compound particles in the 2.0 wt%Li-containing alloy. Although non-ferrous alloys do not exhibit the same close relationship between hardness and tensile strength shown by most steels, the higher hardness does imply that the alloy possesses higher tensile properties. This suggests that low Cu:Mg ratio Al-Cu-Mg alloys containing silver and lithium exhibit promising properties.

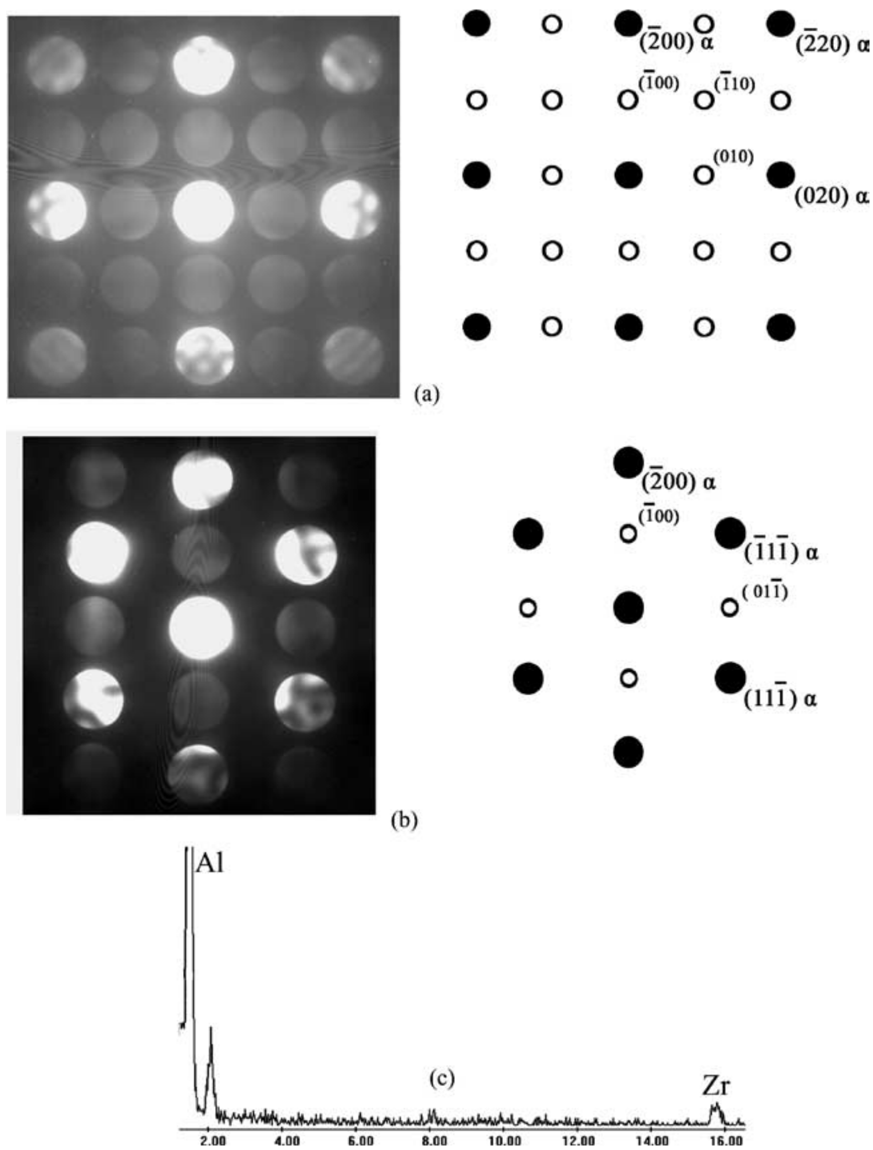

Figure 3 MBED and EDXS analysis of the compound particle precipitated in Al-4Mg-1.5Cu-0.4Ag-2.0Li-0.12Zr alloy aged at 200 °C for 2 h: (a) MBED pattern taken from $\langle 001\rangle_\alpha$ zone axis and corresponding simulated pattern, (b) MBED pattern taken from $\langle 011\rangle_\alpha$ zone axis and corresponding simulated pattern and (c) EDXS spectrum from the inner region of the compound particles.

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