JMEPEG (2010) 19:1235–1239
DOI: 10.1007/s11665-010-9606-4

1059-9495/$19.00

Strengthening and Room Temperature Age-Softening of Super-Light Mg-Li Alloys

Jyh-Shyan Leu, Chih-Te Chiang, Shyong Lee, Yung-Hung Chen, and Chun-Lin Chu

(Submitted July 17, 2009; in revised form November 9, 2009)

Extremely light (density ~1.46 g/cm^3) and highly formable Mg-Li alloys have been drawing research interest; however, their relatively low strength is discouraging, and thus, an issue to be addressed. This paper processes and evaluates four Mg-Li alloys: the first, a basic alloy with a nominal composition of Mg-11%Li-1%Al-0.5%Zn; the second, an alloy with only Be added to the first; the third, an alloy with only Sc added to the first; and the fourth, with both Be and Sc added to the first. This research achieves a high strength of ~240 MPa for Mg-Li alloys using the processes of solid solution treatment plus 90% heavy rolling. A subsequent natural aging process proceeded spontaneously and resulted in strength decay. Room temperature softening behavior is uncommon, but offers a convenient route for studying age-softening characteristics of metallic alloys.

Keywords heat treating, non-ferrous metals, rolling

1. Introduction

Mg-Li alloys are arguably among the lightest materials viable for structural application. For example, a LAZ1110 alloy (Mg-11%Li-1%Al-0.5%Zn) possesses a density of 1.64 g/cm^3, calculated according to the rule of mixture (Ref 1). Surprisingly, actual density is significantly lower and is comparable with plastics. However, its elastic moduli can be at least ten times higher than that of plastics. Another merit is its ease to be cold-worked, making it desirable for sheet, plate, tube and bar structures. Conceptually, Mg-Li alloys might be a good candidate for making parts for an aero vehicle such as the skin of fuselage, wings, and landing frame. For example, they will be tried on unmanned aerial vehicle (UAV).

Previous studies have investigated several Mg-Li alloys mainly containing ~9% Li, and their ultimate tensile strength (UTS) after the extrusion process were well below 200 MPa (Ref 2, 3). According to the Mg-Li phase diagram (Ref 4), a Li content between ~5 wt.% and 11 wt.% indicates that the alloy's structure contains dual phases, $\alpha + \beta$, favorable for superplasticity (Ref 5, 6). This paper focuses on the Mg-11%Li-1%Al-0.5%Zn (LAZ1110), whose nominal structure is single-phase or pseudo-single-phase of β. Hsu et al. reported the room temperature aging characteristic for this Mg-Li alloy (Ref 7). However, aging does not lead to strengthening, so they added Sc to the LAZ1110 to inhibit age softening. Sc is generally considered very effective in refining grain and forming coherent precipitates for strengthening Al alloys (Ref 8). Retaining a minute amount of Be is easy in Mg-Li alloys, because it is a common practice to add a small amount of Be in preparing molten Mg alloys for de-oxygenation and preventing fire hazard.

Jyh-Shyan Leu, Chih-Te Chiang, Shyong Lee, and **Chun-Lin Chu**, Department of Mechanical Engineering, National Central University, Jhongli 32001, Taiwan; and **Yung-Hung Chen**, Chun Shan Institute of Science and Technology, Longtan 32546, Taiwan. Contact e-mail: jenlen.boy@msa.hinet.net.

2. Materials and Experimental

This study prepared four Mg-Li alloys in 200 mm (8″) cylindrical ingots, formed by a vacuum melting process: the first, a basic alloy with a nominal composition of Mg-11%Li-1%Al-0.5%Zn; the second, an alloy with only Be added to the first; the third, an alloy with only Sc added to the first; and the fourth, with both Be and Sc added to the first. The alloys were then homogenized at 350 °C, followed by an extrusion for plates. The listed compositions (Table 1) were determined by Induction Coupled Plasma (ICP)-AES and Spark-OES instruments. Density (Table 2) was obtained by weighing a piece of block (15 mm × 15 mm × 3 mm) from the extruded LAZ110, divided by its associated volume. These plates were subjected to various thermo-mechanical treatments. Specimens from various thermo-mechanical conditions were prepared for room temperature tensile strength tests.

3. Results and Discussion

3.1 Specific Strength of the As-Extruded LAZ110

Table 2 presents the UTS and associated elongations for the four Mg-Li alloys. Their values do not widely differ, indicating that the minute amount of Be and/or Sc does not tailor these two room temperature properties. Since the extrusion was performed at 350 °C, work hardening effect should be minimal. The lower bound of wrought LAZ1110 can be assumed to be

Table 1 Compositions of the Mg-Li alloys studied (wt.%)

Alloys	Mg	Li	Al	Zn	Sc	Be
LAZ1110	Rem	11.2	0.95	0.43	…	…
LAZ1110 + Be	Rem	10.4	1.02	0.66	…	0.017
LAZ1110 + Sc	Rem	10.5	1.15	0.54	0.009	…
LAZ1110 + Be + Sc	Rem	11.2	0.99	0.48	0.012	0.007

Table 2 Strength and ductility of the extruded four Mg-Li alloys and an ordinary Mg alloy AZ91 (Cast)

Alloys	Density, g/cm^3	UTS, MPa	Elongation, %
LAZ1110	1.46	149.6	37.6
LAZ1110 + Be	1.46	152.3	54.8
LAZ1110 + Sc	1.46	153.9	36.6
LAZ1110 + Be + Sc	1.46	159.2	32.1
Cast AZ91C (Ref 9)	1.81	117	0.75

~150 MPa to further determine the specific strength for comparing with other materials, e.g., the most common AZ91C. The lowest specific strength of LAZ1110 is 150 MPa/1.46 = 103 MPa, while a cast AZ91 possessing a density of 1.81 g/cm^3, and strength of 117 MPa (Ref 9) gives a specific strength of 117 MPa/1.81 = 67.6 MPa, almost half of the LAZ1110 in the least strong condition. This high-specific strength of LAZ1110 is attributed to its less stressed super-light characteristics. The density of a solid solution generally lies between the densities of materials that make it up, following a rule of mixtures (an arithmetic mean, weighted by volume fraction). The calculated density for the LAZ1110 is 1.64 g/cm^3, however, the measured value is ~1.46 g/cm^3. The ratio of the measured over calculated density of LAZ1110 is approximately 0.89 (1.46 divided by 1.64). This exceptional and positive discrepancy is due to the structural transformation from h.c.p. (possessed by Mg element) to b.c.c. (Li). Theoretically, the volumetric densities for b.c.c. and h.c.p are 0.68 and 0.74, respectively, so their ratio is 0.918 (0.68 divided by 0.74). Since the weight density ratio of measured to calculate is 0.89, it is close enough to the theoretical volume one to validate the preceding statement.

3.2 Subsequent Strengthening Via the Following Processes

The preceding narrative draws a bottom line for strength level, and incidentally emphasizes the super-light nature of the four LAZ1110s. Based on the underlining strength level, various processing procedures are performed to enhance the level.

3.2.1 Cold Rolling. A feature of the Mg-Li alloy is its ability to be cold-rolled in contrast to other Mg alloys such as the AZ and ZK series. Even the Mg-Li alloys are b.c.c. structured, making them intrinsically easier to receive plastic deformation compared to other general Mg alloys possessing h.c.p. structure. The ability of the Mg-Li to accept up to 90% cold rolling without needing intermittent annealing is exceptional. Four as-extruded Mg-Li LAZ1110 alloys as described above were cold-rolled by 30%, 60% and 90%, and their resulted strengths and elongations are plotted in Fig. 1. Observations show that UTS scales progressively with the extent of rolling. This result agrees with microstructure

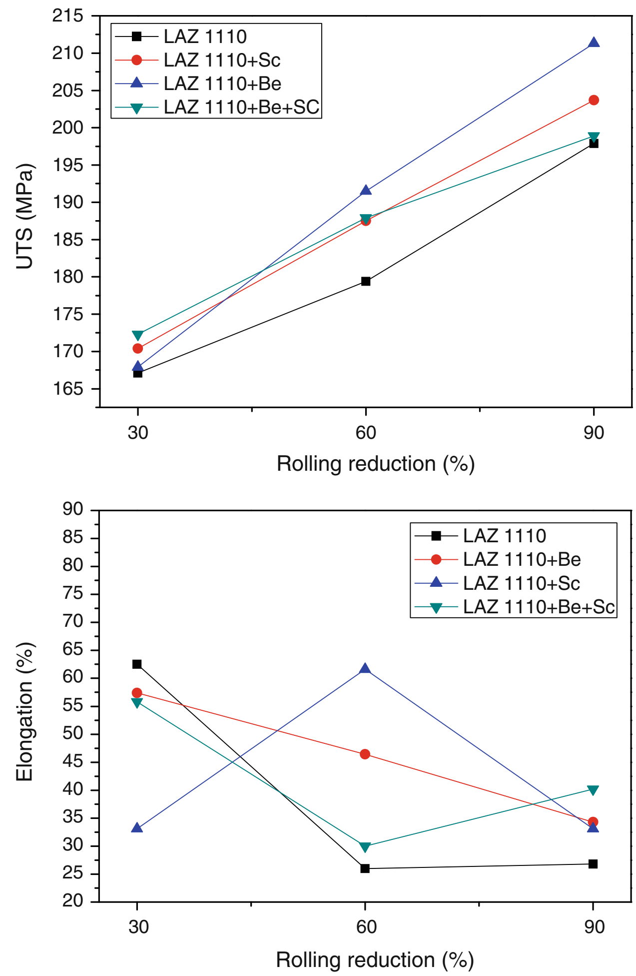

Fig. 1 Strength and ductility of the LAZ1110 alloys as a function of cold rolling reduction (%)

evolution associated with Fig. 2, which depicts texture development as a function of rolling reduction to LAZ1110 + Sc. The amount of α phase (white appearance) also scales in this trend, indicating that the Mg solute dissolving in Li Matrix is meta-stable such that cold rolling can easily squeeze out Mg atoms to form an α aggregate. However, this process does not contribute to strengthening. On the contrary, it leads to softening as will be discussed next.

3.2.2 Solution Treatment. Solution treatment as performed at 350 °C × 1 h followed by water quenching on four alloys. These treatments dissolve pre-existing α precipitates to form a slightly over-saturated solid solution as dictated by the phase diagram (Ref 7), which exhibits a single-phase appearance (Fig. 3). Grain size increases in the pre-treated condition, a typical reaction of a single-phase structure without grain

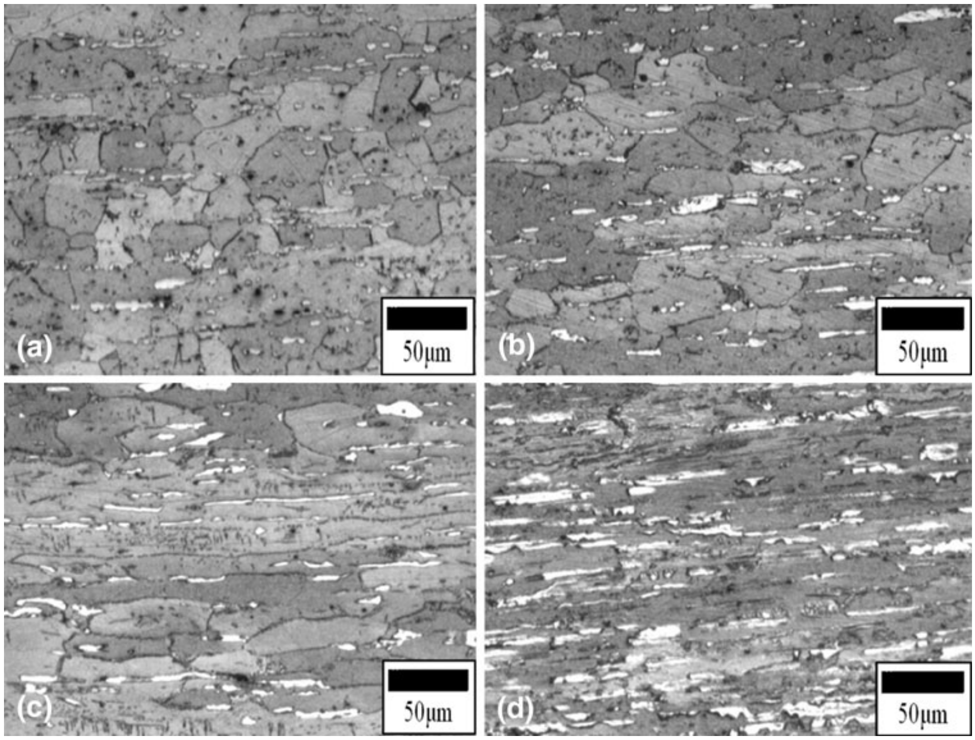

Fig. 2 Optical micrographs of LAZ1110 + Sc subjected to various rolling reductions, (a) prior to rolling, β grain of ~36 μm + ~6.6% small α particles, (b) 30%, (c) 60%, and (d) 90%

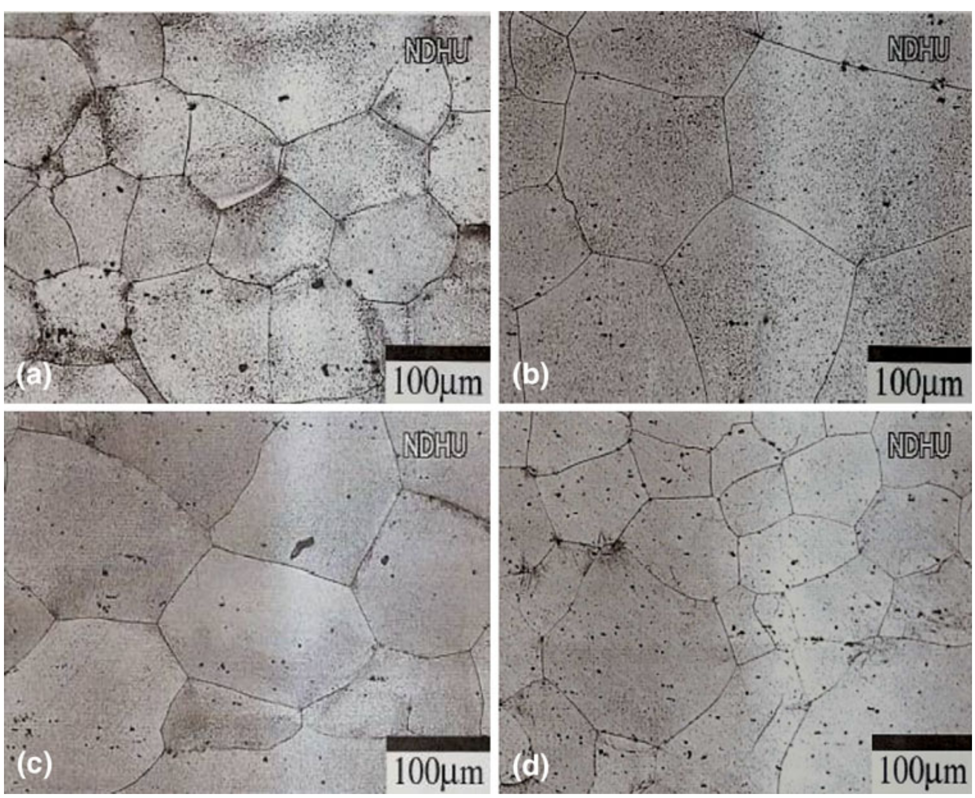

Fig. 3 Optical micro-graphs of solution-treated specimens, (a) LAZ1110, (b) LAZ1110 + Be, (c) LAZ1110 + Sc, (d) LAZ1110 + Be + Sc

boundary obstacles. An XRD examination confirms this structure as it only exhibits β-phase peaks (Fig. 4). Room temperature strengthening due to work hardening, grain boundary, and particle hardening, should be excluded for this kind of structure. This solid solution strengthening (Table 3) is as effective as the 90% cold rolling presented above, which is

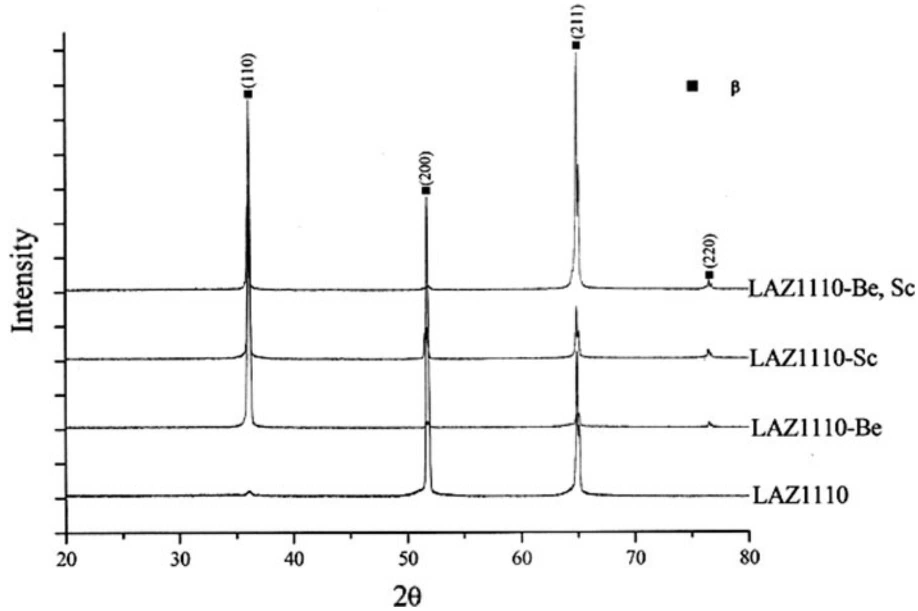

Fig. 4 XRD patterns corresponding to solution-treated specimens

Table 3 Strength and ductility of the solution-treated LAZ1110 alloys

Alloys	UTS, MPa	Elongation, %
LAZ1110	217	21.3
LAZ1110 + Be	210.2	24.8
LAZ1110 + Sc	210.8	25.9
LAZ1110 + Be + Sc	206.4	30.2

Table 4 Strength and ductility after solution treatment plus 90% cold rolling

Alloys	UTS, MPa	Elongation, %
LAZ1110	235	30.5
LAZ1110 + Be	242.2	22.5
LAZ1110 + Sc	240	23.1
LAZ1110 + Be + Sc	238.9	22.4

exceptional as solid solution strengthening is relatively weak (Ref 10).

3.2.3 Solution Treatment Plus Cold Rolling. As presented in the preceding narrative, solution treatment, or heavy cold rolling can equally raise the strength of the extruded state from 150 to ~210 MPa. Combining these two processes is tempting for double strengthening. The specimens were first solution treated followed by 90% cold rolling, showing a paramount strength level of 240 MPa (Table 4). This value is superior to each individual strength obtained by a single separate process, indicating that the effects of two strengthening mechanisms, solution treating, and cold rolling, are additive. Figure 2 shows that rolling texture developed accompanied by α precipitation. The XRD examination showing the emerging α phase due to cold rolling verifies this optical microstructure (Fig. 5).

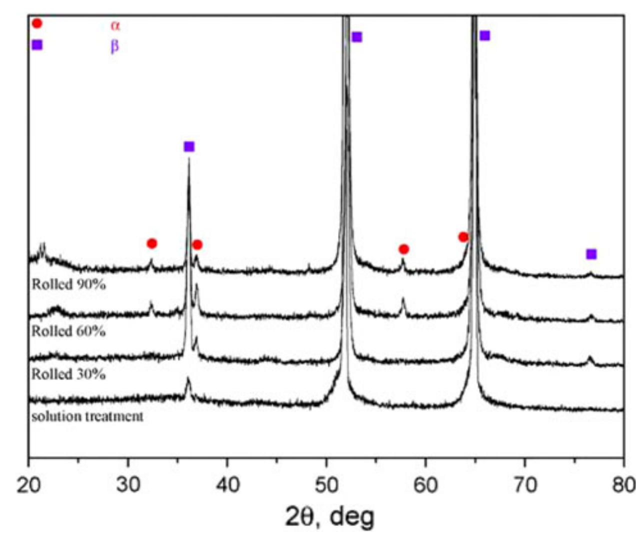

Fig. 5 XRD patterns corresponding to LAZ1110 of four different conditions (from bottom to top): (1) only a single β phase exists following solution treatment, (2) rolled at 30% with light α precipitation; (3) and (4) rolled at 60% and 90% with definite α peaks

Table 5 Strength and ductility after 6 months room temperature aging

Alloys	UTS, MPa	Elongation, %
LAZ1110	185.7	35.7
LAZ1110 + Be	187.4	34.1
LAZ1110 + Sc	190.3	33.7
LAZ1110 + Be + Sc	186	38.1

3.2.4 Age Softening. Although thermo-mechanical treatments have obtained a high level of UTS (240 MPa), all four LAZ1110 alloys show aging effect under a room temperature environment. Table 5 shows that the strengths relax significantly after a time period, e.g., six months, possible due to precipitation. Hsu et al. (Ref 7) reported that room temperature aging proceeds spontaneously following the solution treatment. Deteriorating strength correlates with the α precipitation as informed by optical micrographs and XRD patterns (Fig. 2 and 5). Although the age-softening phenomenon is obvious, its accurate progression is unknown, warranting further study.

4. Summary

This study has launched a comprehensive work on the Mg-Li alloy LAZ1110 and its three derivatives. These alloys are super light, as each individual density is around 1.46 g/cm^3, making their specific mechanical properties exceptional. The general strengthening mechanisms—cold work, solid solution and aging, function within these alloys. The solution treatment effect is especially significant and immediate room temperature natural aging can push up the strength to ~240 MPa. However, extended natural aging continues but leads to softening, and how to block their softening effect is a challenging research topic. Minute amounts of Be and/or Sc, $<0.02\%$, do not play an effective role in this respect.

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