Proceedings of the 9th International Conference on Aluminium Alloys (2004)
Edited by J.F. Nie, A.J. Morton and B.C. Muddle

Development of Al-Cu-Mg-Li (Mn,Zr,Sc) Alloys for Age-Forming

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Keywords: 2xxx alloys, DSC, creep forming, fatigue resistance, toughness

Abstract

Age forming of lower wing skin structures for civil airframes requires an alloy with good age formability and mechanical properties (yield strength, ultimate tensile strength, fatigue resistance, toughness). Using property modelling and general metallurgical understanding, a series of Al-Cu-Mg-Li (Mn, Zr, Sc) alloys have been designed. After artificial ageing representative of age-forming several of the newly designed alloys have yield strength, fatigue crack growth resistance and toughness that are at least comparable to the incumbent damage tolerant material for such applications, *viz.* 2024-T351. Coarse grain structure and high Li content are seen to be associated with good fatigue resistance but reduced formability, and an optimum balance needs to be sought.

1. Introduction

In age forming of aluminium alloys for airframe applications, curved wing skin components are manufactured by mechanically conforming a plate or sheet over a specifically curved tool, with the metal and tool combination then being held (under load) at the alloy's ageing temperature to simultaneously achieve strengthening of the alloy, and creep relaxation of the material into the required curvature. Such processing results in significant manufacturing cost benefits over established methods (e.g. peen forming). Whilst this process is becoming established in upper wing applications, incumbent lower wing skin alloys, such as 2024-T351, loose their critical damage tolerant properties upon ageing. There is therefore a drive to develop new alloys to meet the age formability requirements with mechanical properties (strength, corrosion and damage tolerance) that are at least equivalent to 2024-T351 [1]. In this work, semi-quantitative understanding of microstructure-property relationships has been used to formulate an initial group of potentially age formable alloys. Subsequent extensive analysis of the microstructure [2] and mechanical properties, in combination with modelling of the composition-processing-property relations was used in an iterative process in the development of further groups of alloys [1]. In this paper, selected results from this project are presented, along with basic analysis of the main microstructural parameters affecting the mechanical properties. Key elements of work on the modelling of these relationships are also discussed.

2. Alloy Selection and Property Modelling

The strategy for alloy selection is based on general metallurgical knowledge as well as analysis of a previous batch of alloys studied in this project. Processing-microstructure-properties models were developed during this project and used together with existing models to formulate the alloys. To date a total of 16 alloys based mostly around the Al-Cu-Mg system have been designed. This paper will focus on 8 alloys, as listed in Table 1. It may be noted that Alloys 5 & 6 are close to standard 2024, with Alloy 5 being particularly modified by the addition of Zr and a very small amount of Li.

Table 1: Compositions of the alloys studied.

Alloy	Cu	Mg	Zr	Mn	Sc	Li
3	2.27	1.03	0.11	0.01	-	1.56
4	2.24	0.94	-	0.42	-	1.60
5	4.30	1.46	0.06	0.43	-	0.17
6	4.34	1.37	-	0.42	-	-
7	2.08	0.97	0.11	-	0.21	0.55
8	2.22	0.90	0.11	-	-	0.57
9	1.48	1.43	0.11	-	-	0.54
10	2.10	0.9	0.11	-	-	0.74

2.1 Age Formability/Creep

Many precipitation sequences can occur in Al-Cu-Mg alloys with Li additions (S, θ, Ω, T_1). Generally creep resistance decreases with decreasing solution strengthening and decreasing overall yield strength. Alloys containing a limited amount of fine S'/S precipitates are thought to be suitable for achieving a good balance between the desired mechanical properties and high creep rates that are beneficial for age formability.

2.2 Yield Strength

An age hardening model has been developed to predict the yield strength of Al-Cu-Mg alloys with composition within the α+S phase field of the phase diagram [3,4,5]. Compositions of alloys 2-4 and 7-10 are aimed to achieve a yield strength that does not significantly exceed 2024-T351 yield strength as increasing yield strength is broadly detrimental to toughness in aluminium alloys [6].

2.3 Fatigue Crack Growth Resistance

Fatigue crack closure is beneficial to fatigue crack growth resistance [7]. Crack closure is enhanced by the presence of shearable precipitates and large grains. An analytical model of roughness induced crack closure has been developed to provide semi-quantitative relation between fatigue crack growth (FCG) and microstructural features [8,9]. As underaged alloys generally show a better FCG resistance, alloy design aims at slowing down the precipitation process in these alloys compared to 2024. This can be achieved by reduced Cu+Mg content and also by microalloying with Li and Zr [1].

2.4 Toughness

Coarse intermetallic particles are detrimental to the fracture toughness [6]. Li containing precipitates such as δ' (Al_3Li) have also been reported to be detrimental to toughness due to in-service embrittlement. Therefore, in the alloy formulations, Li additions are low to limit in service δ' formation.

3. Experimental Procedures

Experimental alloys (Table 1) have been manufactured at QinetiQ, Farnborough, UK. Billets were cast, stress relieved, homogenized, hot rolled to 20mm thickness, solution heat treated, cold water quenched and plastically stretched by ~2.5%. Except for solution treatment temperatures, the processing was essentially the same for all alloys (optimum solution temperatures for individual alloys were identified via DSC measurement). To simulate ageing during age forming, heat treatments at 150°C and 190°C were performed. For comparison, commercial 2024-T351 was also tested. All specimens for testing were manufactured from the mid-thickness of the plates.

Tensile tests in rolling direction (L orientation) were carried out according to ASTM E8. Toughness ranking tests was performed on alloys aged for 12h at 150°C and 190°C. Charpy slow bend testing, according to ASTM E-812, was used to define a ‘crack strength’ value which is related to the plane strain fracture toughness of these alloys (however valid data could not be obtained for alloys with low UTS levels, see Section 4). Fatigue crack growth tests were carried out on materials aged for 12h at 150°C and 190°C according to ASTM E-647 using compact tension specimens taken in the LT orientation. Tests were performed in air using a loading frequency of 20Hz and a stress ratio of 0.1.
Age formability was assessed via creep tests conducted for 20h. Tests were conducted in tension with an applied stress of 150MPa at 190°C. Details of DSC, TEM, FEG-SEM and EBSD experiments are presented elsewhere [3,10].

4. Results and Analysis

A wide range of microstructures was obtained in these alloys. The Mn, Zr and Sc additions gave rise to different grain structures, see Figure 1. The Mn-containing alloys 4, 5 and 6 were predominantly found to be recrystallised with coarse grains, whilst the Zr-containing alloys (alloys 3, 8, 9, 10) were only partially recrystallised with smaller grain sizes. A particularly fine grain structure was evident in the Zr and Sc containing Alloy 7.

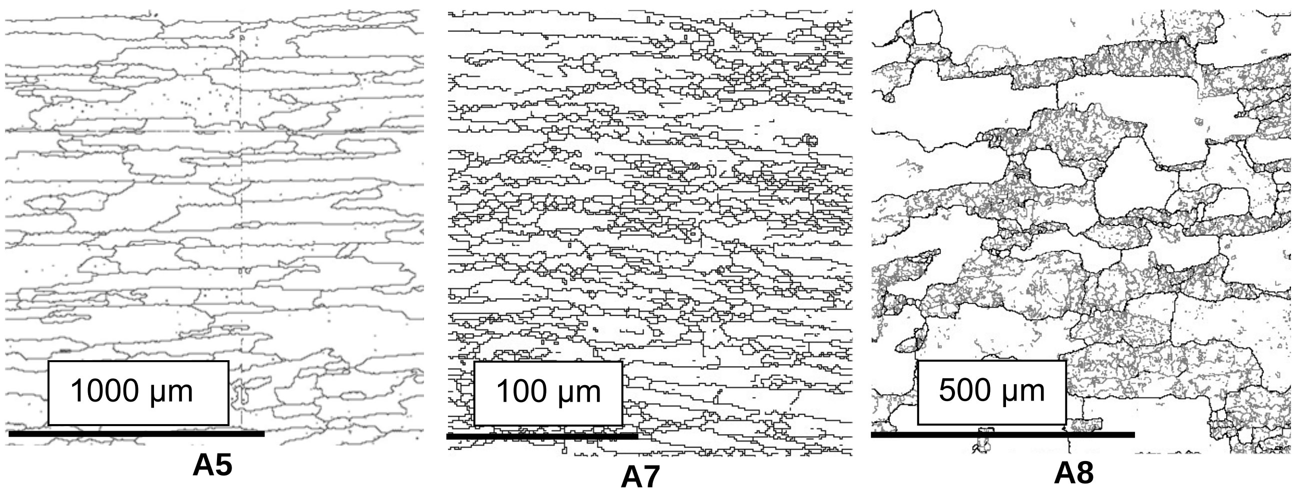
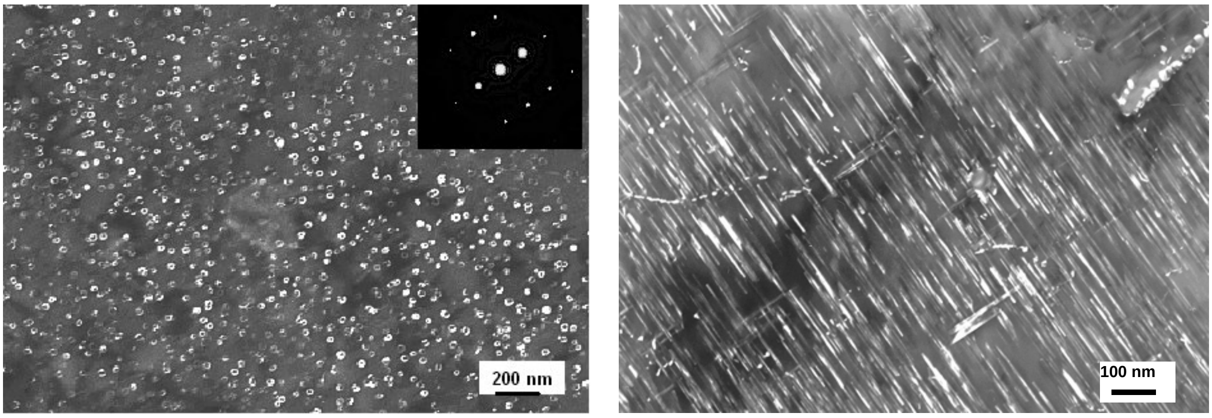


Figure 1: EBSD maps of TS face of alloys 5 (Mn-containing), 7 (Zr+Sc-containing) and 8 (Zr-containing).

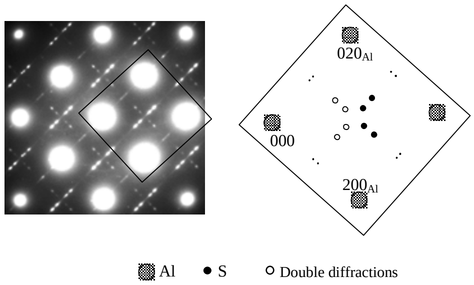
In terms of strengthening precipitates (see Figure 2 and Refs [2-5]) a distinct difference was observed between alloys aged at 150°C and 190°C with the former containing predominantly clusters and the latter S phase. Evidence of some δ' precipitates was found in alloy 3 and 4, with $L1_2$ ordered composite β'(Al_3Zr)/δ' particles appearing in alloy 3.

The ultimate tensile strength (UTS) and yield strength for alloys 3-10 aged at 190°C are shown in Figure 3. Alloys 5 and 6 have a yield strength and UTS that is significantly higher than 2024-T351. Alloys 3, 4, 7, and 8 achieve tensile properties comparable or better than 2024-T351 after ageing. Alloys 9 & 10, with reduced Cu+Mg levels exhibit lower strengths.



(a) **(b)**

Figure 2: TEM micrographs (dark field) of a) alloy 3 aged 72h/150°C (B=[112]) showing composite β'(Al_3Zr)/δ' particles, b) alloy 6 aged 12h/190°C (B=[100]) showing S precipitates, with corresponding SAD pattern.



It should be noted that the strategy devised to slow down the precipitation process, i.e. reduced solute content and microalloying, has been successful as alloys 3, 4, 7, 8, 9 and 10 reach peak strength well after alloys 5 and 6 do. Additional DSC experiments (not presented) confirmed the reduced rate of S phase formation on addition of Li. Measured yield strength results were generally in good agreement with expected yield strength from model predictions [3,4]. Comparison of tensile properties for specimens aged at 190°C and 150°C showed an increased yield strength of up to 100MPa for the alloy aged at 190°C [1]. This means that alloys YS/UTS properties can be 'fine tuned' by adjusting the ageing treatment and/or composition to achieve the target strength properties.

Results of the toughness ranking exercise are given in Figure 4, where crack strength (i.e. toughness), is plotted as a function of yield strength. The Alloys 3 and 7 are seen to perform well, consistent with their fine grain structures and use of Zr or Zr+Sc dispersoids (increasing resistance to shear decohesion). From these results it seems that achieving the desired toughness level is not a limiting factor in the alloy design.

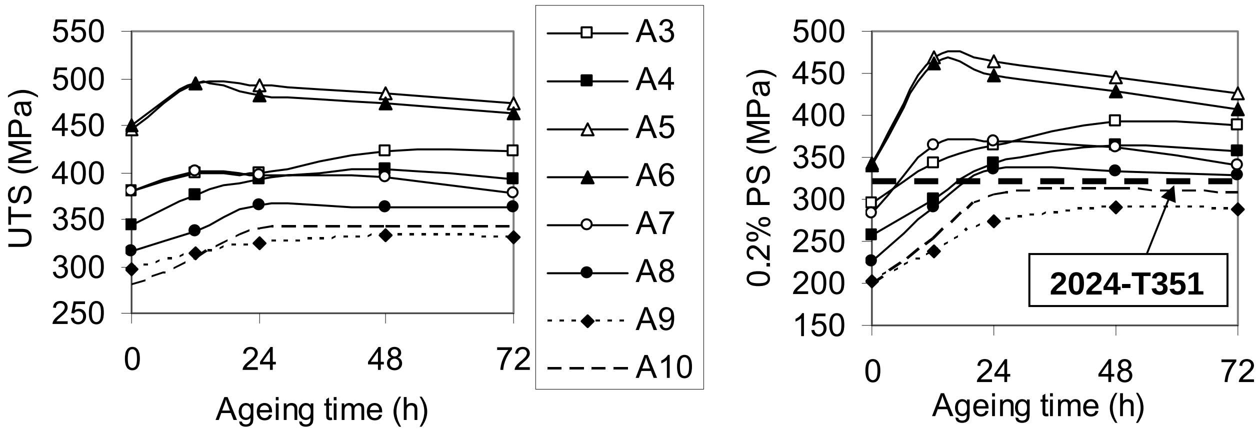


Figure 3: UTS (a) and PS (b) for alloys 3-10 aged at 190°C.

The FCG rates for alloys 3-10 aged at 190°C for 12h are plotted in Figure 5 together with a lower limit for 2024-T351 data. Results of tests performed on specimens aged at 150°C for 12h showed the same relationships between alloys. Alloys heat treated at 150°C for 12h have better FCG resistance than alloys aged at 190°C for 12h, which are closer to peak strength [1]. Figure 5 shows that FCG resistance for all alloys is at least comparable to 2024-T351, except for alloy 7 at intermediate ΔK. The influence of the grain structure was clearly seen: large, recrystallised grains were seen to enhance fatigue performance in alloy 4 compared to alloy 3. This is also highlighted by the relatively poor performance of alloy 7, which exhibits a very fine grain structure. Some detrimental effect of an increased content of non-shearable S/S′ precipitates content in alloy 5 is suggested when compared to alloy 4, see Figure 5.

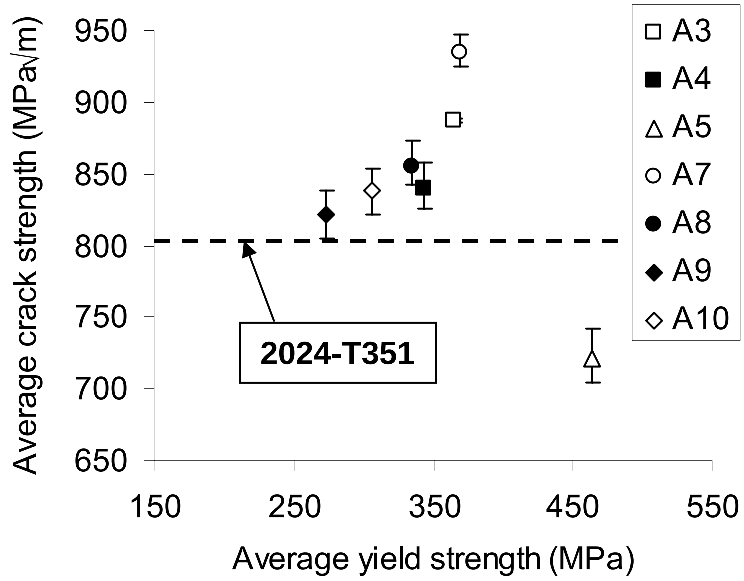


Figure 4: Crack strength for alloys 3,4,5,7,8,9 and 10 aged at 190°C for 12h compared to 2024T351.

However, this difference can also be influenced by the difference in Li content. Though the effect of Li is not explicitly separated in these alloys, a beneficial effect of increased Li content may also be suggested here. Within the group of alloys assessed, there is clear evidence of microstructural influence on crack growth behaviour. The relative effect of crack closure on the fatigue performance of the different alloys is discussed elsewhere [8,9].

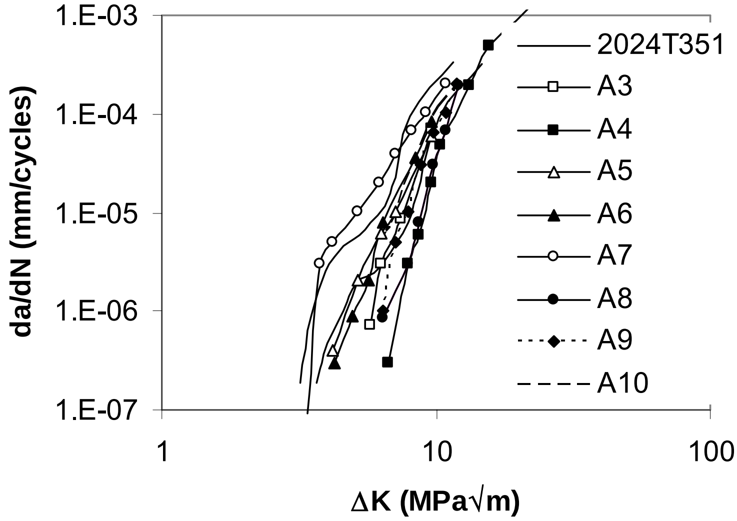


Figure 5: Fatigue crack growth rate vs ΔK for alloys 3-10 aged at 190°C for 12h.

Figure 6 shows the results of creep tests performed on alloys 3, 4, 5, 7 and 8 at 190°C at a stress of 150MPa. A range of creep rates is observed. Again the grain structure appears to be a first order influence, with the smallest grain size alloy (A7) exhibiting the highest deformation. However, other parameters have to be considered, with comparison of alloy 4 and 5, and alloy 3 and 8 suggesting a detrimental effect of Li on formability.

In general the creep rates for the present under aged alloys are comparable to creep rates of other alloys used in commercial age forming operations (particularly 7xxx-series), and hence the present alloys may be considered to be age formable.

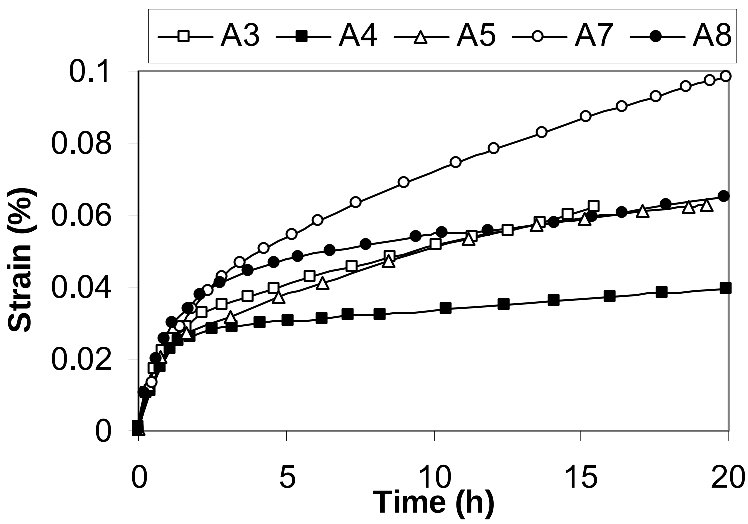


Figure 6: Creep tests results for alloys 3, 4, 5, 7, 8 at 190°C at a stress of 150MPa.

5. Concluding Remarks

So far, results show that after artificial ageing simulating age forming the 3 main properties (yield strength, FCG resistance and toughness) of several of the new alloys are at least comparable 2024-T351. The only property that degrades for the new alloys relative to the incumbent material is the ultimate tensile strength. Current work is aimed at alleviating this. Influences on the overall property balance have been identified, and especially the balance between formability (as identified from creep rates) and fatigue crack growth resistance is important. The balance is especially influenced by grain structure and Li content. The current results indicate that there is a clear potential for damage tolerant age-formed structures using newly defined alloys, provided the balance between composition and forming conditions is fine tuned to give the right properties and the cost of the new alloys is competitive.

Acknowledgements

The authors would like to acknowledge the financial support from EPSRC, QinetiQ and Airbus UK.

References

[1] M.J. Starink, I. Sinclair, N. Gao, N. Kamp, P.J. Gregson, P.D. Pitcher, A. Levers and S. Gardiner, Mater. Sci. Forum, 396-402, 601-606, 2002.
[2] N. Gao, L. Davin, S. Wang, A. Cerezo and M.J. Starink, Mater. Sci. Forum, 396-402, 923-928, 2002.
[3] M.J. Starink and J. Yan, Proc. of 1st International Symposium on Metallurgical Modelling for Aluminium Alloys, ASM Materials Solutions 2003, October 12-15, 2003, Pittsburg, PA, USA.
[4] M.J. Starink, N. Gao, L. Davin, J. Yan and A. Cerezo, submitted to Acta Mater.
[5] J. Yan and M.J. Starink, Proc. of ICAA9, these proceedings.
[6] N. Kamp, I. Sinclair and M.J. Starink, Metall. Mater. Trans., 33, 1125-1136, 2002.
[7] Y. Xu, P.J. Gregson and I. Sinclair, Mater. Sci. Forum, 331-3, 1473-78, 2000.
[8] N. Kamp, M.R. Parry, D.S. Singh and I. Sinclair, Acta Mater., 52, 343-353, 2003
[9] N. Kamp, M.R. Parry, N. Gao and I. Sinclair, submitted to Metall. Mater. Trans. A.
[10] M.J. Starink and S.C. Wang, Acta Mater., 51, 5131-5150, 2003.