DEVELOPMENT OF THERMALLY STABILISED ALUMINIUM-LITHIUM SHEET FOR FUSELAGE APPLICATIONS

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ABSTRACT: Aluminium-lithium alloy sheet is currently used for a weight critical military aerospace applications, but uptake by the civil market has required further technical improvements. It was thought that such materials could typically provide a 10% weight saving over conventional fuselage materials, such as 2024-T3, they have sustained unacceptable reductions in plasticity on account of nucleation and/or growth of δ' (Al_3Li) and/ or GPB zones taking place on thermal exposure. A new alloy ALFSOTATS (Aluminium Lithium Fuselage Sheet Optimised for Toughness and Thermal Stability) was developed which combines dilute composition and a novel heat treatment to produce a material of a superior fracture toughness than 2024-T3, both before and after considerable thermal exposure; ALFSOTATS sheet strength derives primarily from a dense background of very fine δ' precipitates, yet their growth after considerable thermal dose (2000 at 90°C) was insufficient to drop K_{c0} below 160MPam$^{1/2}$ Theoretical ALFSOTATS properties were subsequently made for a 30 year thermal profile and revealed that though fracture toughness would decline, this would only be to a level comparable with clad 2024-T3 (i.e. K_{c0}=150MPam$^{1/2}$). On this basis, use of Al-Li alloy on a civilian pressurised fuselage may now become feasible.

Keywords: Aluminium-lithium, toughness, thermal stability.

1. INTRODUCTION

The origin of the poor fracture toughness resilience of aluminium-lithium alloys on thermal exposure lies in the metastability of the alloy matrix, which retains relatively high concentrations of lithium in solid solution after typical one-stage heat treatments, conducted at ~70°C below the δ' (Al_3Li) solvus temperature. During a typical life-time, the aircraft fuselage is exposed to temperatures significantly below that of the solvus, that favour further δ' nucleation/growth, and therefore increment matrix order strengthening. As the strength increases, plastic deformation becomes limited and fracture toughness is reduced, often to an unacceptable level. Sufficient thermal stability of aluminium-lithium sheet products will only be achieved by stabilisation/ prevention of such δ' growth.

A new aluminium-lithium alloy, ALFSOTATS, has been developed which features lower Li and Mg contents than the established 8090 (Al-2.4Li-1.2Cu-0.7Mg-0.06Zr) and would intuitively be predicted to feature less δ' and S' (Al_2CuMg) phase strengthening, for a given ageing practice; the new alloy also offers an ~8% density reduction by comparison with the incumbent 2024-T3 material. In order to attenuate 'in service' strengthening of ALFSOTATS sheet, a multiple stage Retrogressive Step-Wise (RS-W) heat treatment was adopted, which included a dwell at a temperature well below the δ' solvus that would maximise Li removal from super saturated solid solution (SSSS). The RS-W practice was designed to reduce the nucleation and/or coarsening rates of δ' during typical 'in service' fuselage sheet life, by comparison with those sustained by alloys, heat-treated closer to the δ' solvus.

2. MATERIALS AND METHOD

Large-scale casting of Aluminium-lithium billet to a relatively dilute composition within the F92 8090 Al-Li patented range (Al-2.0-2.8Li-1.0-1.5Cu-0.4-1.0Mg) was made and material processed into 1.6mm thick sheet, following proprietorial processes to optimise stretch delay, level of stretch and RS-W treatment. Thermal exposure of 1.6mm thick sheets was carried out within an air circulating oven at 90°C for ALFSOTATS and 2024-T3 sheet and at 70°C for 8090 for durations ≤6000h.

Tensile testing was were carried out in accordance with BS EN10002-1, for LT orientation non-proportional test pieces, and elongation was measured over a 25 mm gauge length. Crack growth resistance R-curves were established for the unexposed and 90^0C exposed materials using 2 m wide test panels, in the T-L orientation with a length to width ratio (L/W) of 0.5; all panels were supported with anti-buckling plates during the tests. An initial centre-crack length of 0.3W was simulated using a saw cut, sharpened to 0.5 mm wide for the last 10 mm, and panels were loaded under displacement control at a rate of 2 mm/min. The residual toughness (K_{CO}) was determined, to ±3% accuracy, from the initial crack length and the maximum applied gross stress and where possible, the critical stress intensity factor, K_C, have been determined from the maximum gross stress and the effective crack length at which maximum stress occurred.

Fractographic analysis of RS-W and thermally exposed fracture toughness specimens was carried out using a LEO 360 SEM, operated at 20kV at 10 mm physical crack extension. Energy filtered TEM/HREM was performed using a 200kV Hitachi HF-2000 TEM, fitted with a Field Emission (FE) source and a Gatan Imaging Filter (GIF), whilst conventional TEM utilised a 120kV Philips EM-420 TEM. Sample preparation in both instances was carried out by electropolishing to perforation at -20°C using a Tenupol twinjet polisher, using a 30%HNO_3/70%CH_3OH electrolyte and at a p.d. of 20V.

3. RESULTS AND DISCUSSION

The performance of ALFSOTATS sheet is summarised in Table 1, which also includes control data on the, thermally resilient, 2024-T3 and also RS-W treated 8090.

3.1. Unexposed alloy sheets

In this condition, ALFSOTATS RS-W sheet was fairly weak (0.2%PS~230MPa) by comparison with 2024-T3 (0.2%PS~297MPa) but had a very high fracture toughness; the extreme plasticity of the ALFSOTATS panels caused nett section yield before failure, but realistic K_{c0} values were ~160MPam$^{1/2}$ and represented a ~14% toughness improvement over (the minimum) 2024-T3 value measured in this work (Table 1). TEM/HREM examination of this sheet revealed a widespread distribution of fine δ' precipitates, of diameter (d)=3.9±1.0nm (Figs 1 and 2) which were surrounded by a completely disordered α matrix. In such samples, there was neither evidence for ultrafine-scale non-stoichiometric $L1_2$ zones/ domains nor Al-Cu-Mg GPB zones, which might otherwise strengthen/ stabilise the alloy. By comparison, 8090 RS-W was found to contain larger, d=6.2±1.3nm, δ' precipitates (Fig. 3), concomitant with the alloy's greater Li concentration. Both these aluminium-lithium sheets sustained failure by transgranular mode (Fig. 4), which would be expected of a damage tolerant Al-Li alloy temper.

Sheet	**Exposure Time**	**Temp**	**E**	**$R_{P0.2}$**	**R_m**	**A**	**K_{CO}**	**K_C**
	h	°C	GPa	MPa	MPa	%	MPa √m	MPa √m
2024-T3	0	--	-	296	421	19	140	186
2024-T3	4000	90	66.4	297	427	23	143	187
2024-T3	6000	90	-	301	424	22	145	197
ALFSOTATS	0	--	73.3	227	340	15	149*	-
ALFSOTATS	1000	90	75.2	258	374	18	155	208
ALFSOTATS	1000	90	75.3	267	377	15	155	206
ALFSOTATS	2000	90	77.1	274	387	18	161	207
ALFSOTATS	4000	90	76.5	288	396	15	140	177
ALFSOTATS	4000	90	78.9	281	397	14	148	193
ALFSOTATS	6000	90	79.5	290	404	17	141	180
8090 -T81	0	--	76.1	309	433	13	115	130
8090 (RS-W)	0	--	78.8	268	409	15	152	189
8090 (RS-W)	4000	70	73.8	293	428	16	129	155

Table 1 Alloy mechanical properties with and without thermal exposure for 1.6mm sheet; K_c measured for 2m wide panels l/w=0.5 (T-L). * nett section yield before failure.

3.2. Experimental thermal exposure

After 1000h exposure at 90°C, ALFSOTATS sheet proof stress increased by 30MPa, though fracture toughness remained superior to that of 2024-T3. The principal strengthening increment in ALFSOTATS sheet was identified as δ' growth, to d= 6.0±1.0nm, and this was accompanied by dislocation loop/ spiral creation as a consequence of vacancy condensation, on δ' development. There was however only limited evidence for S' precipitation/ GPB zones.

After 2000h exposure at 90°C, ALFSOTATS sheet had sustained further strengthening, though K_{c0} (161MPam$^{1/2}$) remained higher than 2024-T3. After 4000h exposure, 0.2%PS had increased to 281-288MPa and K_{c0} had been reduced to 148-140MPam$^{1/2}$, though this value remained comparable with that of 2024-T3. It was subsequently established that this sheet had sustained a final RS-W heat treatment stage that was 5°C higher than intended and this may well have caused excessive δ' growth and concurrent fracture toughness drop. The longest exposure at 90°C (6000h) incremented ALFSOTATS 0.2%PS to 290MPa and reduced its K_{c0} to 141MPam$^{1/2}$; sheets featured enlarged δ' precipitates and also limited S' phase, though insufficient quantities were present to offer significant Orowan strengthening. HREM revealed δ' precipitates as large as 11nm, but typically of d=8.0±1.0nm diameter, which derived from growth and/or coalescence of δ' (Fig. 5), from the RS-W treatment. These enlarged precipitates were surrounded by a completely disordered α matrix. In other regions of the specimen, small quantities of fine domains , of d <4.5nm, were observed which were identified as stoichiometric δ' phase.

After 4000h thermal exposure at just 70°C, 8090 RS-W had sustained a 15% decrease in fracture toughness to level significantly below that of either 2024-T3 or ALFSOTATS, in RS-W or any of the thermally exposed conditions investigated.

Fracture surfaces of ALFSOTATS and 8090 sheets of all thermal doses were similar and featured rough and stable crack growth, which had occurred by transgranular shear with *roof-top* features dominating the surfaces (Fig. 6). Clearly, failure had occurred by slip localisation in the slip bands, which ultimately fractured.

This isothermal exposure work has shown that ALFSOTATS sheet primarily exploited its low strength, by comparison with 8090, to retain a plane stress condition and therefore high levels of toughness even after considerable isothermal exposure. By contrast, 8090 RS-W failed to retain a plane stress condition, causing fracture toughness to be reduced to a level below that of 2024-T3, after only a modest (4000h, 70°C) thermal exposure. The RS-W heat treatment may have reduced the solubility of Li in the matrix, c.f. conventional one stage treatments, but it could not prevent δ' phase developments and concomitant toughness reduction, on thermal exposure. Although this reduction was only to 2024-T3 toughness levels, the lack of any plateau in the ALFSOTATS thermal exposure data suggested a propensity for further growth of δ' and therefore loss of toughness.

3.3 Lifing issues

In service, fuselage skin temperature can fall to -55°C, or even lower and may also be raised as high as 90°C [1]. Since the loss of toughness of ALFSOTATS sheet with thermal exposure is eventually inevitable, it becomes vital to establish whether sheet would be sufficiently resilient over a typical aircraft lifetime, exposed to the more representative temperature profile. Theoretical predictions have been made of proof stress over a 30 year period which calculate sheet response to a series of thermal exposure dwells over a monotonically increasing temperature range; fracture toughness (K_{c0}) values were then inferred from Fig. 7, which was constructed from an experimental database of results previously collected for 1.6mm thick aluminium-lithium sheet. This simplified model provides a more realistic indication of ALFSOTATS property development than the single temperature treatments investigated experimentally.

From the isothermal experimental TEM and tensile data, coarsening was found to obey the $0.2\%\text{PS} \propto t^{1/6}$ relation and therein confirmed that δ' coarsening in ALFSOTATS obeyed Lifshitz-Slyozov-Wagner (LSW) kinetics, for Ostwald ripening, wherein

$$d^3 - d_0^3 = 8k(t - t_0) \qquad \text{-1-}$$

where d_0= initial δ' diameter, k=coarsening constant; $t-t_0$ = thermal exposure duration; k=coarsening constant, calculated as $3.35\times10^{-33}\text{m}^3\text{s}^{-1}$. ALFSOTATS sheet painted dark red would have the greatest propensity to age hardening and its response over a typical lifetime was calculated on the following assumptions:-

i) strength incrementation is by δ' coarsening, and thus increasing order strengthening, and remains described by the LSW theory at the lower temperatures;

ii) Diffusion of Li is the rate limiting step of δ' coarsening and has an activation energy=120kJmol^{-1};

iii) The initial 0.2%PS was ≈242MPa, i.e. a relatively strong starting condition.

Table 2 shows that dark red ALFSOTATS sheet sustains age hardening, but after 30 years of representative thermal doses (including 15 years on-the-ground desert storage), 0.2%PS reached only 259MPa, for which $K_{c0}\sim150\text{MPam}^{1/2}$ and compared favourably with 2024-T3.

Total Time ($\times10^8$s)	Interval ($\times10^7$ s)	Temp (K)	K_c (m^3s^{-1})	K_ct (m^3)	δ' radius (nm)	crss (MPa)	0.2% PS (MPa) LT	K_{c0} ($MPam^{1/2}$) T-L
0	0	--	--	--	1.95	43.5	242	>160
1.58	15.8	253	1.48E-40	2.34E-32	1.95	43.5	242	>160
5.13	35.5	293	3.1E-37	1.1E-28	1.96	43.6	243	>160
5.92	7.88	295.1	4.37E-37	3.44E-29	1.96	43.7	243	>160
6.31	3.94	298	6.96E-37	2.75E-29	1.96	43.7	243	>160
6.71	3.94	303	1.52E-36	6.01E-29	1.97	43.7	243	>160
7.10	3.94	308.5	3.5E-36	1.38E-28	1.98	43.9	244	>160
7.49	3.94	312.5	6.29E-36	2.48E-28	1.98	44.1	244	>160
8.09	5.91	317.2	1.23E-35	7.27E-28	2.03	44.2	245	>160
8.48	3.94	325.3	3.72E-35	1.47E-27	2.17	44.7	247	>160
8.68	1.97	330.5	7.37E-35	1.45E-27	2.27	45.2	248	>160
9.07	3.94	334.5	1.23E-34	4.84E-27	2.55	47.2	255	155
9.27	1.97	336	1.48E-34	2.92E-27	2.69	48.5	259	150

Table 2: Predicted properties for cyclic exposure of red fuselage; crss=critical resolved shear stress.

4. CONCLUSIONS

From an industrial perspective, ALFSOTATS sheet subjected to the RS-W heat treatment has been shown experimentally to preserve plane stress toughness levels that were at least comparable with 2024-T3 even after prolonged isothermal exposure. In addition, high toughness has been predicted to remain after a more realistic 30 year thermal dosage profile that would be sustained by the pressurised fuselage. It is noted that although the ALFSOTATS composition and RS-W treatment still produce sheet which sustains age hardening, via growth of δ' precipitates, material retains sufficient levels of damage tolerance to make use of aluminium-lithium on pressurised fuselage applications now feasible.

5. REFERENCES

[1] Price H.J., BAe Airbus Report R+T/134510/95018 (1995).

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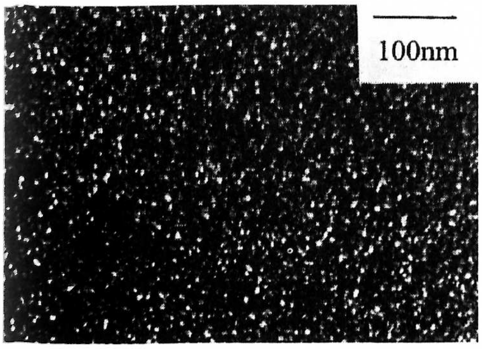

Figure 1 ALFSOTATS RS-W DF image of δ' distribution

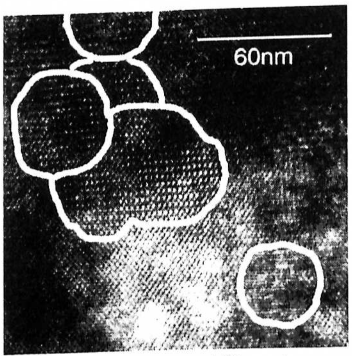

Figure 2 HREM of δ' and α matrix in ALFSOTATS RS-W

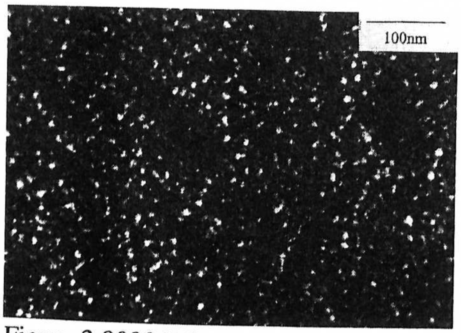

Figure 3 8090 RS-W DF image of δ' precipitation

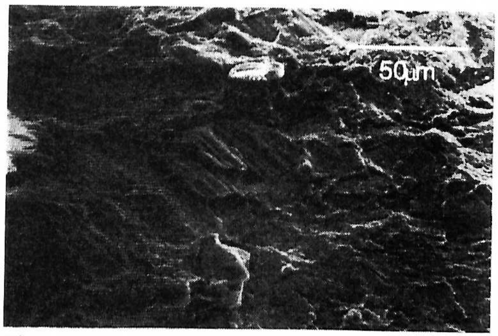

Figure 4 ALFSOTATS RS-W fracture surface

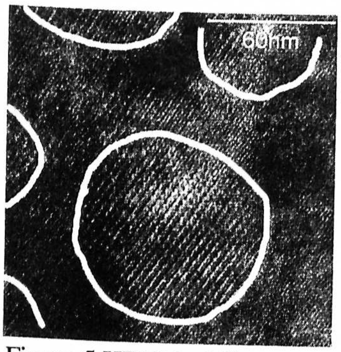

Figure 5 HREM of δ' and α matrix ALFSOTATS RS-W+6000h, 90°C

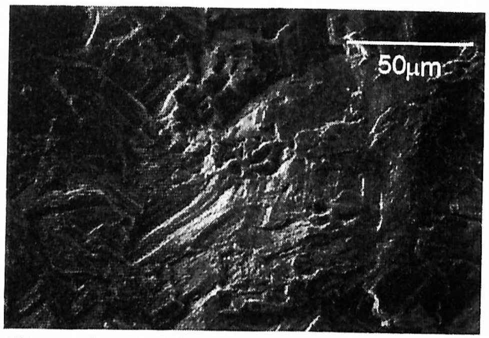

Figure 6 ALFSOTATS RS-W+6000h, 90°C fracture surface

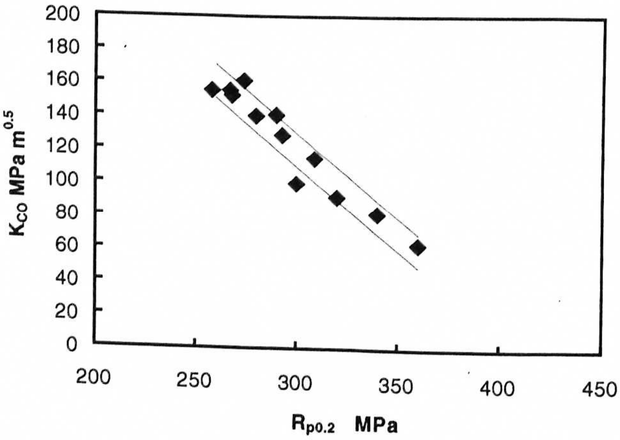

Figure 7 Variation of K_{c0} with 0.2%PS for 1.6mm thick Al-Li sheets