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Low-energy intergranular fracture in Al–Li alloys ☆

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ABSTRACT

An age-hardened Al–Li–Cu–Mg–Zr alloy (AA8090) used for a substantial part of the structure of a helicopter (in order to save weight) exhibited low-energy intergranular fracture during accidents, resulting in extensive damage. With this experience in mind, various hypotheses for brittle intergranular fracture in Al–Li alloys are reviewed, and possible remedial measures outlined. The effects of variables such as alloy composition, ageing times and temperatures, crystallographic texture, and test temperature on brittle-intergranular-fracture resistance are described, and it is concluded that lithium segregation to grain boundaries is primarily responsible for brittle intergranular fracture. Lithium segregation occurs mainly during the primary ageing treatment; but secondary ageing during service, where temperatures can reach 50–80 °C, could increase lithium segregation and further increase susceptibility to brittle intergranular fracture. The evidence also suggests that the prevalence of a planar-slip-mode in Al–Li alloys, resulting in dislocation pile-ups at grain boundaries, is not responsible for brittle intergranular fracture, contrary to widespread opinion.

1. Introduction

The use of aluminium–lithium alloys in aerospace structures is attractive owing to their lower density and higher stiffness compared with conventional aluminium alloys, with each 1 wt.% Li (~4 at.%) reducing density by ~3% and increasing stiffness by ~6%. A wide variety of Al–Li alloys have been developed over the years [1–7], and the compositions and densities of some of the more well-researched alloys are listed in Table 1.

The 2xxx and 8xxx alloys are produced by the ingot-metallurgy route, and ingots are rolled, forged, or extruded, producing a largely unrecrystallised pancake-shaped grain structure. These alloys are age-hardenable, with peak strengths up to 700 MPa, and the type and morphology of age-hardening precipitates depend on the alloy composition and ageing treatment [8,9]. The 8090 alloy, which is the main focus of the present paper, is strengthened by spherical, coherent, $L1_2$ δ' (Al_3Li) matrix precipitates and, to a lesser extent, by lath-shaped S′ (Al_2CuLi) matrix precipitates. Coherent β' (Al_3Zr) phase precipitates are also present and act to inhibit grain growth. Lithium-rich precipitates nucleate and grow preferentially at grain boundaries during ageing leading to a solute-depleted precipitate-free zone (PFZ) adjacent to the grain boundaries (Fig. 1). There is also some evidence that lithium segregation occurs at grain boundaries between grain-boundary precipitates (GBPs) [10–15].

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Table 1
Typical (mid-range) compositions (wt.%) of some common Al–Li alloys.

	Li	Cu	Mg	Zr	Others
8090	2.3	1.2	0.7	0.12	
2090	2.0	2.8		0.1	
2297	1.2	3.0		0.1	
2195	1.0	4.0	0.3	0.14	0.3Ag
5091	1.3		4.1		1.17C, 0.41O

Al–Li alloys have not been as widely used as was anticipated during the alloy-development programmes in the 1980s; and, in fact, there has not been any large-scale use of these alloys in commercial aircraft to date, as far as the authors are aware. The reluctance to use Al–Li alloys stems partly from the greater tendency for anisotropic properties and low-energy intergranular fracture as compared with conventional Al alloys, but the continued improvement in the properties of conventional Al alloys [16] has also been a factor. Brittle intergranular fracture in Al–Li alloys is more prone to occur in alloys with higher lithium contents (especially >2 wt.%), and in product forms with elongated grain structures stressed normal to the short-transverse crack-plane orientation [12–15].

There have been some successful applications of Al–Li alloys, such as use of the weldable 2195 alloy for the external tank of the space shuttle [17]. Another significant (but arguably less successful) use of Al–Li alloys (8090) has been for the fuselage skin, stringers, and frames of Agusta–Westland EH101 helicopters [18–21], see Fig. 2. (These helicopters have been given different names in different countries, e.g. Merlin in UK, Cormorant in Canada.) The fracture toughness of the near-peak-aged 8090 alloy was presumably considered to be adequate at the time it was selected, but helicopters that crashed or had heavy landings after a number of years in service suffered extensive damage, indicating that the fracture toughness was low [22,23].

Examination of the near-peak-aged 8090-T852 forgings from a crashed helicopter [22,23] showed that the microstructure was as expected (Fig. 3) and that cracking had occurred along grain boundaries with little sign of macroscopic or microscopic deformation (Fig. 4) (although shallow dimples are sometimes observed at high magnifications). These fracture surface characteristics are similar to those observed during alloy-development programmes for near-peak-aged 8090 die forgings [19] and 8090-T8771 alloy plate [12], especially for S-L crack-plane orientations, and are normally deemed unacceptable. Hence it is possible that exposure of the forgings to somewhat elevated temperatures in service (50–80 °C) for long (accumulated) times (months/years) could have increased the susceptibility of the material to low-energy (brittle) intergranular fracture. This is discussed in detail in a subsequent section.

Various reasons have been proposed for the tendency of Al–Li alloys to exhibit brittle intergranular fracture, but no consensus has been reached. Obviously, a better understanding of brittle intergranular fracture in Al–Li alloys might suggest ways of minimising the problems and contribute to future development of alloys with improved toughness. Thus proposed explanations for brittle intergranular fracture are outlined in the following section. The pros and cons of these explanations are then summarised in the light of the effects of variables, such as alloy composition, ageing condition, crystallographic texture, and test temperature, on fracture characteristics. Some comparisons of the fracture behaviour of Al–Li alloys with that in other materials are also summarised, since such comparisons are particularly enlightening. Finally, some comments are made regarding lessons to be learnt from the use of Al–Li alloys in helicopter structures and the future of Al–Li alloys.

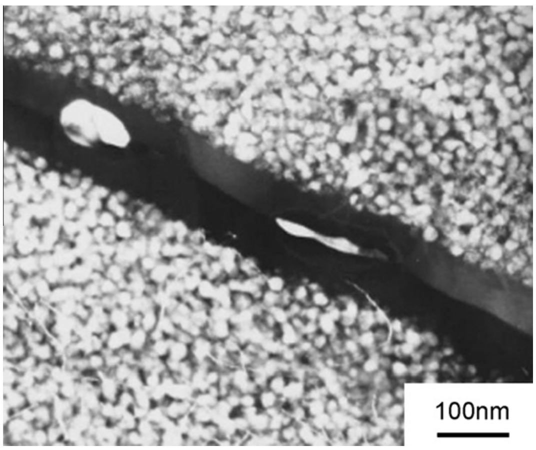

Fig. 1. Dark-field TEM of near peak-aged 8090-T8771 alloy showing matrix precipitates, grain-boundary precipitates, and a precipitate-free zone.