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Quantification of the influence of increased pre-stretching on microstructure-strength relationships in the Al–Cu–Li alloy AA2195

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ABSTRACT

The effect of increasing pre-stretching to higher levels, than are currently used in industrial practice, has been investigated on the strength, microstructure, and precipitation kinetics seen during artificial ageing an Al–Cu–Li alloy AA2195 - focussing on the behaviour of the main strengthening phase, T_1. Increasing the pre-strain level, to the maximum obtainable before plastic instability (15%), resulted in an increase in the T8 yield strength to ~ 670 MPa with a corresponding reduction in ductility from ~11 to 7.5%. Microstructure data have been used to deconvolute and model the effects of increasing pre-strain on the main strengthening components that contribute to this large strength increase. The precipitation strengthening model proposed by Dorin et al. [1] has been successfully employed to calculate the strengthening contribution of the T_1 phase and the increase in strength due to strain hardening has been modelled using X-ray line broadening measurements of dislocation density, using the modified Williamson–Hall approach. Refinement of the T_1 phase was observed to continue to higher pre-strains than previously thought, but it is predicted that this leads to a reduction in the strengthening contribution from precipitation. In contrast a low level of recovery was observed during stretching, and artificial ageing, resulting in an increasing contribution form strain hardening with pre-strain. Thus, it is shown that increasing the pre-strain prior to ageing results in a reduction in the strengthening provided by the T_1 phase, in favour of an increase in the strain hardening contribution.

1. Introduction

Third generation (Gen3) aluminium-lithium (Al–Li) alloys [2] are of great interest to the aerospace industry owing to a number of key benefits they offer over conventional aluminium (Al) alloys [3–5]. In particular, their lower density, excellent corrosion resistance, and combination of higher fatigue performance, high strength and toughness, can lead to significant weight savings. They also offer a cost advantage over CFRPs (Carbon Fibre Reinforced Polymers) which has led to Gen3 Al–Li alloys being increasingly substituted for conventional 2xxx and 7xxx series materials in new aircraft designs [6].

Previous generations of aluminium-lithium alloys contained a higher concentration of lithium (Li) and had a lower density than the new Gen3 alloys. However, these earlier alloys suffered from high anisotropy, lower toughness, and manufacturing issues, associated with the high Li level and precipitation of the metastable δ′ and coarser equilibrium Li containing phases, such as T_2 [3,5,7]. New Gen3 alloys typically contain lower Li levels of 1–1.8 wt.%, which suppresses δ′ formation, and have chemistries designed to promote T_1 as the dominant strengthening phase. These developments have proved to be extremely effective in providing high strength without the deleterious effects seen in the previous generation [1,8–10].

The conventional manufacturing route for aluminium aerospace plate involves a stretching operation after solution heat treatment, to relieve the large residual stresses developed on quenching, during which the material is typically plastically strained between 2 and 5% [11]. In Gen3 alloys this stretching operation is also critical to obtain an optimum distribution of T_1 precipitates, which are dislocation nucleated. It has been widely shown that a small pre-strain prior to artificial ageing produces a uniform distribution of dislocations within the matrix, which act as heterogeneous nucleation sites for the T_1 phase [8–10]. This results in the nucleation of a fine homogeneous distribution of the T_1 phase throughout the material during artificial ageing, leading to exceptional mechanical

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performance [5,8,12,13]. Stretching also serves to accelerate matrix precipitation and thus avoid competition with grain boundary precipitation, which leads to a detrimental effect on toughness [14]. The exact nucleation mechanism is still under debate, but is known to involve prior segregation of Cu and Mg to dislocation lines [15].

The T_1 (Al_2CuLi) phase has been extensively studied and is known to form as very thin semi-coherent hexagonal plates with a $\{111\}_{Al}$ matrix habit plane [16–18]. T_1 precipitates have a particularly high aspect ratio and provide a greater hardening effect than the θ′ phase, which forms as octagonal plates on $\{100\}_{Al}$ planes [8,19]. As it is dislocation nucleated, increasing the pre-strain increases the density of T_1 nucleation sites and the resultant finer precipitate distribution reduces the average diffusion field size, so the matrix is depleted of solute in a shorter timescale. This results in accelerated ageing kinetics with increasing values of pre-strain. However, the benefits of stretching have been widely reported to saturate at pre-strains of around 6–9% in Al–Cu–Li alloys [8,9].

The T_1 plates were originally thought to be shear resistant [20]. In contrast, recent research by Deschamps et al. [1,21] has demonstrated that T_1 precipitates are cut by dislocations during plastic deformation, across the entire range of conventional ageing treatments, as the plates are very thin (~1.3 nm) and their thickness is very stable with ageing time at temperatures below ~ 170 °C [21–23]. Dorin et al. have proposed a strengthening model for the T_1 phase, based on earlier work of Nie and Muddle [24], that considers the interfacial and stacking fault energy contributions to a $\{111\}_{Al}$ habit plane, plate-shaped, precipitate's shear resistance. This model has been demonstrated to be able to reliably predict the yield strength contribution of the T_1 phase in a 2198 alloy for a wide range of plate dimensions and densities [1]. However, in this work, although it was reported that after ageing the alloy's yield stress was relatively constant for pre-strains greater than about 2% [1], the contribution of dislocation forest strengthening to the alloy's yield stress was not explicitly measured. It was also proposed that after recovery the residual strain hardening caused by pre-stretching compensates for a predicted reduction in precipitate strengthening, due to the reduced plate diameter that results from an increase in precipitate density with rising levels of pre-strain, and there is thus a coincidental linear correlation between strength and particle volume fraction in this alloy system.

Recent developments in rolling control technology can enable the production of plates with variable thickness that offer potential benefits in the production of nearer-to-net-shape sections; for example in the manufacture of tapered wing skins. One significant implication of applying this processing technology is the subsequent impact on the required stretching operation. The stretching of a tapered plate results in a strain gradient and for Al–Cu–Li alloys the maximum strain that can be achieved without tensile fracture limits the taper that can be utilised without omitting the critical stretching step. It is therefore important to better understand the impact of increasing plastic pre-strains, to near the plastic limit, on the peak-aged microstructure found in Gen3 plates and ultimately how this impacts on the materials peak yield strength and other mechanical properties.

While much prior work has been carried out to investigate the effects of increasing pre-strain on precipitation strengthening in Al–Li alloys within standard limits, there has been less published on the effects of more extreme stretching operations. The work presented here thus aims to examine the effect of increasing tensile pre-strains, to near the tensile plastic limit, on a typical Gen3 Al–Li alloy's ageing kinetics, microstructure and yield strength. It is also considered that, according to classical theory, higher pre-strains should perhaps lead to dynamic recovery and the formation of a dislocation cell structures [25]. This, in turn, could potentially cause microstructural heterogeneity by affecting the distribution of the T_1 phase. The effect of thermal treatment during artificial ageing, on reducing the strain-hardening contribution to the materials strength by dislocation recovery, is also currently largely unknown. Ultimately, this could have a profound impact on the mechanical properties of the alloy and how the different strength contributions relate to the overall peak yield strength of the material.

The work presented here thus aims to examine the effect of increasing tensile pre-strains, to near the tensile plastic limit, on a typical Gen3 Al–Li alloy's ageing kinetics, microstructure and yield strength. To this end, tensile tests, hardness testing and Differential Scanning Calorimetry (DSC) have been employed to explore the effect of higher pre-strain (i.e. above 6%) on a AA2195 alloy's ageing kinetics and yield stress, while simultaneously utilising the modified Williamson–Hall X-ray diffraction (XRD) peak broadening analysis to measure the effect on the residual dislocation density. Transmission electron microscopy has also been used to determine the effect of the pre-strain on the dislocation structures and to quantify the dimensions and distribution of the T_1 phase. This data has then been utilised to model the different strengthening contributions that contribute to the alloy's measured yield strength, as a function of the level of pre-strain applied prior to artificial ageing.

2. Experimental method

A typical Gen3 Al–Cu–Li alloy, AA2195, provided by Constellium Voreppe Research Centre in France, was used in this investigation. The alloy was supplied as 22 mm thick plate in a T841 temper. The composition range of AA2195 is provided in Table 1.

Tensile samples were cut from the ¼ plate depth and machined in accordance with BS EN ISO 6892-1:2009 [26]. Each test sample was given a solution heat treatment (1 h at 510 °C) and water quenched. The majority of the samples were then naturally aged to a stable condition (24 h at room temperature; designated here as T4) before pre-straining, by tensile stretching, to plastic strain values ranging from 3 to 15%, (designated here as T3) and then being subjected to artificial ageing. The upper limit of 15% was selected after analysis of the work hardening rate in the T4 condition, which indicated that this was the maximum strain that could be reliably used while avoiding plastic instability. Some samples were also tensile tested immediately (within 10 min) after solution treatment and quenching (designated STQ).

Pre-stretching and tensile testing was carried out using an MTS Alliance RT/100 tensile machine at a strain rate of 2 mm/min, with the strain being monitored by a 25 mm clip gauge extensometer. The required plastic pre-strain values were produced by elongating the tensile samples in the T4 condition. Artificial ageing was performed with an initial heating ramp of 20 °C per hour, followed by an isothermal hold at 150 °C for a range of times up to 100 h. Following artificial ageing, the pre-stretched tensile samples were tested to failure to measure the effect of a pre-stretch on the material's tensile properties.

The effect of pre-strain on the ageing kinetics was first determined by measuring hardness curves, after applying varying degrees of pre-strain ranging from 3 to 15% to the T4 samples, using an Instron RT100 machine with a V044 indenter and a 0.5 Kg load. An average of five measurements was taken for each condition. Differential Scanning Calorimetry (DSC) analysis was also

Table 1
Nominal composition of AIRWARE alloy AA2195 (wt. %).

	Cu	Li	Mg	Zr	Mn	Ag	Al
Min.	3.70	0.80	0.25	0.08	–	0.25	Bal
Max.	4.30	1.20	0.80	0.16	0.25	0.60	Bal