The influence of artificial ageing on the corrosion behaviour of a 2050 aluminium–copper–lithium alloy

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ABSTRACT

The influence of artificial ageing on the corrosion behaviour of the recently developed 2050 Al–Cu–Li aluminium alloy in chloride-containing solutions was studied. Corrosion tests showed that artificial ageing changed the corrosion morphology of the alloy from intergranular to intragranular and decreased the corrosion potential of the alloy. Transmission electron microscopy observations combined with small-angle X-ray scattering measurements were used to establish a link between the distribution of T_1 precipitates and the corrosion behaviour.

1. Introduction

Reducing the weight of aircraft metallic structures is a current challenge for the aeronautic industry. Due to the increased use of composite materials, the aluminium industry has developed a new generation of aluminium–copper–lithium alloys as an alternative solution. The addition of 1 wt% lithium has been shown to induce a 3% decrease in the density and a 6% increase in the Young modulus [1]. Therefore, the replacement of 7xxx alloys in aircraft metallic structures by Al–Cu–Li alloys, which have similar mechanical properties [2], could induce a 6% reduction in weight. Further weight reductions could be achieved if the additional benefits of these alloys such as increased damage tolerance are properly considered.

Al-Cu-Li alloys are precipitation-hardening alloys; the main strengthening phases can be T_1 (of nominal composition Al_2CuLi), those of the θ' sequence (with its metastable precursors) (Al_2Cu), T_2 (Al_5Li_3Cu), T_B (Al_7Cu_4Li), S (Al_2CuMg) and δ' (Al_3Li). Other slow diffusing elements are added to these alloys to form dispersoid particles such as Al_3Zr and $Al_{20}Cu_2Mn_3$, which are helpful in controlling the grain size during homogenisation and hot rolling [3]. The competition between these different phases is closely linked to the lithium and copper content, minor solute element content [4,5] and the thermomechanical history of the alloy. Cassada et al. [6] studied the nucleation mechanism of T_1 precipitates and proposed that T_1 particles nucleate preferentially on dislocations and at sub-grain boundaries. In another study [7], they showed that plastic deformation before ageing promoted T_1 nucleation. This result was confirmed by Gable et al. [8], who found that plastic deformation before ageing at 160 °C promoted T_1 nucleation at the expense of the aforementioned precipitates. Chen and Bhat [9] proposed a time temperature precipitation diagram for 2195 Al–Cu–Li alloys and showed the predominance of T_B precipitates at high temperatures. Therefore, the mechanical properties of such alloys can be optimised by adjusting the thermomechanical treatment [10].

However, the electrochemical behaviour of these precipitate phases differs from that of the matrix; therefore, their presence in the alloy can have a significant effect on the corrosion behaviour of Al–Cu–Li alloys. The corrosion behaviour of T_1 precipitates has been widely studied in sodium chloride solutions [11–13]. These studies showed that the T_1 precipitates have a more negative corrosion potential than the matrix and were associated with dissolution phenomena such as intergranular corrosion when they were present at grain boundaries [14]. Thus, the thermomechanical treatments applied to these alloys influence the corrosion behaviour by altering the precipitate microstructure. Henon and Rouault

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studied the corrosion behaviour of 2050 alloy as a function of tempering and showed a susceptibility to corrosion in underaged conditions, desensitization near peak age and re-sensitization in overaged conditions [15]. The susceptibility to exfoliation corrosion of an Al–Cu–Li alloy in two different metallurgical states (T6 and T8, *i.e.*, peak aged, with and without predeformation) was studied by Li et al. [16]. When the alloy was in T6 state, it presented great susceptibility to exfoliation corrosion, whereas susceptibility was more limited in its T8 state (predeformed). The authors attributed the exfoliation susceptibility of the T6 state to the presence of a large amount of coarse T_1 precipitates at grains boundaries. Kertz et al. [17] demonstrated that the corrosion morphology of an Al 2.69% Cu 1.8% Li alloy was modified by an ageing treatment. At temperatures greater than 450 °C, the alloy was only susceptible to pitting. However, between 300 °C and 400 °C, the alloy was susceptible to both intergranular and pitting corrosion. Lastly, at lower temperatures, a long ageing treatment was necessary to sensitise the alloy to intergranular corrosion. The authors attributed the modification of the corrosion morphology to the presence of T_1 precipitates at grain boundaries and to the width of the precipitate-free zone (PFZ). Moran et al. [18] studied the exfoliation susceptibility of a 2199 (Al 2.3 wt% Cu 1.4 wt% Li) alloy using various accelerated corrosion tests. Considering that the alloy was exposed to the seacoast for 4 years, the T3 state (no artificial ageing) and the T8 state (peak aged with predeformation) presented good resistance to corrosion, whereas the intermediate metallurgical states were more susceptible to exfoliation corrosion. Moreover, other studies showed that an ageing treatment not only affected the corrosion susceptibility and morphology but also the corrosion kinetics. Jiang et al. [19] measured the average and maximal depths of the corrosion damage in an Al–Cu–Li alloy and found that these two parameters increased with an increase in the ageing time and temperature. The authors explained this phenomenon by considering that an increase in the ageing time or temperature led to an increase in the size of the T_1 precipitates and affected the precipitate-free zone (PFZ).

In summary, the existing literature shows that the corrosion behaviour of Al–Cu–Li alloys is closely linked to the distribution of T_1 precipitates. However, a definitive relationship between the distribution of T_1 precipitates and the corrosion behaviour has not been determined. To establish such a relationship, one should consider different T_1 microstructures by varying the thermomechanical treatments without altering the other characteristic features of the microstructure, such as the grain size, internal stresses of solute segregation to grain boundaries, because these modifications are known to influence the corrosion rate [20–25].

In the present work, we performed a detailed study on the corrosion behaviour of 2050 alloy samples after different ageing treatments and varied the intra- and inter-granular precipitate distribution. Moreover, we related the observed corrosion morphology and kinetics to a systematic characterisation of the precipitates. In parallel to the corrosion morphology observations, the corrosion kinetics in a chloride containing solution was evaluated by obtaining cross-section and residual strength measurements. The global electrochemical behaviour was evaluated using current–potential curves and open circuit potential measurements. The precipitate microstructure was characterised by combining transmission electron microscopy observations and small-angle X-ray scattering measurements.

2. Experimental

2.1. Material

The material studied in the present work was a recently developed aluminium–copper–lithium AA 2050 alloy (Al base, 3.5% Cu,

1% Li, weight percentage) provided by Constellium (France). The material consisted of 20-mm thick rolled plates of the T34 metallurgical state, which was solution treated, stretched and naturally aged. To study the influence of ageing treatments on the corrosion behaviour of AA 2050, samples were aged at 155 °C for 30 h at a heating ramp of 20 °C/h. In the following text, samples in the T34 metallurgical state and aged samples are referred to as NHT (non-heat treated) and HT (heat-treated), respectively. For some experiments, intermediate ageing times at 155 °C were also investigated (1, 2, 3, 5, 9 and 18 h). The grain structure was studied by analysing the optical micrographs on an Olympus PMG3 after etching with Keller's solution (1 mL of hydrofluoric acid 40 wt%, 1.5 mL of hydrochloric acid 35 wt%, 2.5 mL of nitric acid 68 wt% and 95 mL of distilled water). Table 1 provides a summary of the grain information. For all of the samples, the grains were elongated in the rolling (longitudinal) direction. Their mean size, which was measured in the three characteristic planes of the plate, was identical, regardless of the ageing treatment.

2.2. Study of the corrosion behaviour

All of the corrosion tests were performed in 0.7 M NaCl, which was prepared by dissolving Normapur chemical salts in distilled water. The solution was stirred and opened to air, and the temperature was maintained at 25 °C using a Julabo refrigerated circulator. The corrosion behaviour of the samples was studied using conventional immersion tests and stationary electrochemical techniques. For immersion tests, the longitudinal – longitudinal transverse (L-LT) plane of 1 cm-ridge cubic samples was exposed to the electrolyte, while the other planes were protected with a varnish. After immersion, the samples were cleaned with ethanol and dried. The samples were used to characterise the corrosion damage (Fig. 1a, the procedure is provided later in this section). Tensile samples were also submitted to immersion tests (Fig. 1b). The surface exposed to the electrolyte was the L-LT plane, which corresponded to the gauge length and a width of 5 mm. The edges corresponding to the other planes were masked with a varnish. After the immersion test, the samples were cleaned with ethanol, dried and submitted to a tensile test to evaluate the change in the mechanical properties due to corrosion damage and to evaluate the propagation depth of the corrosion damage [26]. For the electrochemical measurements, a three-electrode electrochemical cell was used, including a platinum grid with a large surface area as the auxiliary electrode and a saturated calomel electrode (SCE) as the reference electrode. All of the potentials quoted in the manuscript are with respect to the SCE reference. The working electrode corresponded to one of the previously described samples. The surface exposed to the electrolyte was the L – LT plane and possessed a surface area of 0.785 cm² (1-cm diameter disk). Open circuit potential (OCP) measurements were performed for approximately 2 h. The OCP values corresponded to average values calculated during the last 15 min of the test. Current–potential curves were also plotted. The anodic and cathodic parts of the curves were plotted separately. For the anodic part, the sample was maintained for 5 min at OCP; then the potential was switched to OCP − 5 mV and immediately scanned to −300 mV/SCE. For the cathodic part, the sample was maintained for 5 min at OCP; then the potential

Table 1
Grain size in the three characteristic directions of the rolled plate for the 2050-T34 (NHT) aluminium alloy: longitudinal (L), longitudinal-transverse (LT) and short-transverse (ST).

Direction	L	LT	ST
Grain size (µm)	620 ± 60	310 ± 45	40 ± 20