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Effect of actual and accelerated ageing on microstructure evolution and mechanical properties of a 2024-T351 aluminium alloy

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ABSTRACT

This paper presents an investigation on the effects of ageing on the microstructure and the corresponding physical and mechanical properties of a 2024 aluminium alloy used in a civil transport aircraft wing structure in order to assess the residual resistance of the end of a service life. More precisely, heat treatments are applied in order to simulate thermal ageing actually endured by the structure during service. The results of characterisation of microstructural, physical and mechanical properties are compared not only to the data obtained on a pristine alloy, but also to the results obtained on coupons of a similar alloy coming from the teardown of an A320 aircraft using the same experimental procedure. The main findings are that, during a service life, no significant modification in fatigue resistance is noticed despite of changes in the precipitation structure.

1. Introduction

Due to the increasing number of civil transport aircrafts that come close to the end of the initial design life, airliners as well as aircraft manufacturers have to face different challenges. Indeed, in addition to the life extension concerns, the development of an enhanced knowledge of the structural health during life is a key issue in order to manage the fleet in service, but also to improve the design of new aircrafts. With this respect, the French National program DIAGNOSTAT, sponsored by an Inter-ministerial Fund and endorsed by Aerospace Valley competitiveness cluster, was undertaken with the global objective of getting a feedback on the aircraft structural health at the end of the initial design life and of developing innovative non-destructive techniques to monitor this structural health. The study presented here is more particularly concerned with the first point, and with the ageing effect on the properties of the 2024-T351 aluminium alloy.

The first objective of this study was to compare the residual mechanical properties of an alloy coming from the teardown of wing panels of a decommissioned AIRBUS A320 aircraft with those of a pristine alloy in relation with modifications in microstructure and physical properties. Indeed, as the metastable material constitutive of the aircraft wings have to withstand complex load and/or temperature history (that are generally ill-known), ageing effects on mechanical properties like tensile [1] and fatigue resistance [2–4] cannot be excluded. However the knowledge of the residual performances when approaching the end of the service life, and in particular of the fatigue resistance, is still extremely limited [5–7]. For instance, using a positron annihilation spectroscopy approach, Nicht et al. [8] found no difference between a virgin 2024 alloy and a similar material coming from a A300 aircraft after 18 years of service. In addition the scarce results available in open literature especially about fatigue properties are somehow contradicting. Indeed, while Scheuring and Grandt [6] and Everett [5], considering the fatigue resistance of 2XXX and 7XXX alloys coming from structural parts of various retired or active aircrafts in the US, noticed no substantial difference with handbook data, Basov et al. [9] report a significant decrease in fatigue strength in similar alloys coming from Russian aircrafts. The prime novelty of the work presented in this paper is therefore twofold. The first one is to compare data collected on a material that has experienced many years of real operating conditions with those obtained on a similar alloy artificially aged in laboratory conditions while the second one is to cross the results of mechanical testing with those of different techniques tracking the microstructural evolution induced by ageing. A secondary objective of the study is therefore to assess the actual degree of ageing of the material from teardown. With this aim, artificial ageing treatments have been applied on a pristine material. The relation between microstructure and mechanical properties has then been investigated at different ageing conditions using the same methodology, based on a

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Table 1
Artificial ageing time of 2024-T351 aluminium alloy at 150 °C, equivalent to aircraft ageing life at 80 °C. Grey colour = service life of the aircraft.

Artificial aging at 150°C	Aircraft aging at 80°C
t_0	0 h
t_{27}	50,000 h
t_{55}	100,000 h
t_{80}	145,000 h
t_{177}	319,676 h

characterisation of microstructural modification by SEM and TEM examination and conductivity measurements on the one hand and on the assessment of the impact of ageing on the mechanical properties by mechanical testing (hardness, tensile and fatigue tests) on the other hand. The data collected on artificially aged material are then compared to the information obtained on the material issued from teardown.

2. Experimental techniques and methods

2.1. Material

The pristine material used as a reference in this study was a 2024 T351 aluminium alloy provided in the form of a 50 mm rolled sheet. The final microstructure of the alloy was composed of grains elongated along the rolling direction (L) with an average grain dimension of 700 µm in the longitudinal direction. More details and fatigue data about this material are given in [10]. To evaluate the ageing stage of the 2024 alloy coming from the wing panels, artificial ageing treatments were performed on samples from the pristine material (Table 1). Artificial ageing treatments corresponded to heat treatments carried out at 150 °C for durations comprised between 0 and 177 h. The durations of the treatment were actually calculated on the basic assumption that ageing is controlled by the diffusion of copper atoms, and by considering an equivalence rule between the duration and the temperature of the heat treatment [11]. The aim was to reproduce exposure of an aircraft at a mean temperature of 80 °C for a maximum duration of 319,676 h, i.e. more than 30 years. Typically, using this rule, a 100,000 h exposure at 80 °C corresponded to the service life of an aircraft. Chemical composition of the wing panel alloy and of the pristine material are given in Table 2. One can observe differences in chemical composition between the wing panel alloy and the pristine material, in particular for the copper content. However, Shih et al. [12] showed that, for 2024 aluminium alloy, the major parameter for the precipitation of S' phase was the value of a pre-ageing strain and not the alloying contents. Further, Richard et al. [13] studied the fatigue behaviour of 2022 and 2024 alloys. They showed that the two alloys presented a similar fatigue behaviour in the propagation step despite of their differences in copper content. Therefore, it was assumed here that the different samples, i.e. wing panel samples and pristine samples, could be compared.

As regards more precisely the material aged under actual service condition, the work presented here was concerned with the intrados panels of the A320 aircraft with the Manufacture Serial Number MSN004. This aircraft was operated for 38,637 flights (35,342 h) over 21 years. The material constitutive of the intrados panels is a 2024 aluminium alloy; it had been introduced in the T351 metallurgical state, i.e. solution heat treatment at 495 °C (+/-5 °C), water quenching, straining and then tempering at room temperature for 4 days. Two zones of the wing, shown in Fig. 1, were examined. The first one was located at the tip of the wing (samples designated as W_T) and did not endure severe mechanical loading while the second area, which was placed close to the engine (samples called as W_E), was assumed to sustain higher mechanical loading and maybe exposure to higher temperatures susceptible to generate microstructural modifications. The samples were taken from the plane of the aircraft wing at a considerable distance from the panel fixation in order to avoid the effect of cold expansion at the riveting points.

Table 2
Chemical composition of the wing panels and of the pristine material (wt.%).

	Al	Cu	Mg	Mn	Fe	Si	Ti
Pristine material	Balance	4.46	1.44	0.61	0.13	0.06	0.03
Wing panels	Balance	3.98	1.32	0.66	0.07	0.07	0.02

The wing panels under study were originally fabricated from laminated plates, in such a manner that the longitudinal orientation of the grains is collinear with the longitudinal direction (L) of the wing. Optical observations of the wing panels after Keller's etching revealed grains elongated in the longitudinal direction; a strong heterogeneity was noticed in the grain sizes, with dimensions varying from 100 µm to 1 mm in the longitudinal direction.

2.2. Characterization of the microstructure and of the fracture surface

Optical microscope (OM) observations of both wing panels and pristine materials revealed the presence of coarse intermetallic particles. Observations carried out with a field emission gun scanning electron microscope (FEG SEM-7000F from JEOL with the incident electron beam maintained between 10 kV and 15 kV) combined with analyses performed with an SDD Bruker X flash energy dispersive X-ray spectrometer (EDX) allowed the coarse intermetallic particles to be more accurately characterized and analyzed. SEM observations were also used for the analysis of the fracture surface obtained after tensile tests and fatigue tests (see below) for the samples from pristine, artificially aged and wing panel material.

Concerning the microstructure, transmission electron microscope (TEM) observations from a JEOL-JEM-2010 were also performed to characterize the fine precipitation, i.e. hardening precipitates. The samples were obtained by removing 300 µm thick slices from the wing panels or the artificially aged pristine material. The slices were ground down to approximately 100 µm thick and a dimple was machined in the central region. Final electron transparency was obtained by ion milling on a precision ion polishing system (PIPS(tm), Gatan) using 5 kV Ar^+ ions.

2.3. Conductivity measurements

Conductivity measurements were performed by using an Elotest B300 apparatus combined with a CSCAN mapping software. The evaluation of the conductivity was based on Foucault current measurements. Before testing the samples, the apparatus was calibrated using three reference samples with conductivity equal to 17.1, 21.1 and 24 $MS \times m^{-1}$, respectively. The sample geometry was similar to that of the reference samples, i.e. $4 \times 4 \times 5\ mm^3$ parallelepipeds. Frequency was fixed at 30 kHz in order to achieve a penetration depth around 1 mm. At least 5 measurements were performed for each sample to check the reproducibility of the data. Mean values are given; the scattering of the results was no more than 0.1 $MS \times m^{-1}$.