

Preserving Aviation Heritage: The Need for an Approach Based on Materials Analysis

Magali Brunet, Luc Robbiola, Philippe Sciau, Monique Drieux-Daguerre

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Preserving Aviation Heritage: The Need for an Approach Based on Materials Analysis

Magali Brunet*
CEMES-CNRS
Université de Toulouse
Toulouse, France
magali.brunet@cemes.fr

Luc Robbiola
Laboratoire TRACES UT2J
Université de Toulouse – CNRS
Toulouse, France
robbiola@univ-tlse2.fr

Philippe Sciau
CEMES-CNRS
Université de Toulouse
Toulouse, France
philippe.sciau@cemes.fr

Monique Drieux-Daguerre
Materia Viva
Toulouse, France
materia-viva@orange.fr

*Author for correspondence

Abstract

Most of the metals used in aircraft construction are aluminium alloys. These alloys, poorly investigated for conservation purposes, require specific characterisation due to the presence of intermetallic precipitates at various length scales influencing mechanical properties and resistance to corrosion, and because of different surface treatments. This study undertook an investigation into the different aluminium alloy parts of a currently renovated Breguet aircraft and, as a result, revealed the need to research and characterise these materials. An adapted methodological approach was used and the results of the materials characterisation focused on the main materials and on the corroded surfaces. Alongside performing material analysis, archival documents were used to provide additional and complementary historical data. From this, it was concluded that a specific understanding of the alteration processes in aluminium alloys is required in order to develop conservation strategies.

Keywords

industrial heritage, aeronautical materials, aluminium alloys, multiscale analysis

Introduction

Preserving the industrial heritage of the 20th century presents many challenges. The conservation of old aircraft is one of them. Around the world, there are about 40 air and space museums with dedicated sheds and many more private collections which are managed by different associations. In most cases, aircrafts are kept outdoors which very often leads to the corrosion of metal parts (Rocca et al. 2010). To ensure the safety of visitors and to present aircrafts as they would have once appeared, corroded parts are replaced rather than restored. As a consequence, the original parts of old aircrafts disappear little by little without any traceability.

In this context, there is a real need to study these old materials, mainly for two important reasons. Firstly, for historical purposes: although industrial archives on aeronautical materials exist, technical documents were often not systematically preserved. Secondly, the study of the metal parts of an old aircraft allows damage to be understood by identifying the degradation processes. This helps to ensure long-term conservation. Corrosion is an important source of damage to these cultural heritage materials that needs to be clearly understood prior to deciding conservation protocols.

This study presents the investigation carried out to attain these objectives by analysing the different metallic parts from a 1950s' aircraft undergoing renovation.

Method of study and sampling

For several years, the research team has been following the renovation of a big carrier airliner – a Breguet 765 Sahara no. 504 64-PH (wing span: 45.5 m; length: 29 m; height: 10.15 m; dry weight: 15 t) – which is a part of the aircraft collection preserved by the Ailes Anciennes Toulouse association. This collection represents aeronautical adventure and local industrial history. The Breguet 765 (Figure 1a), a double-decker aircraft built in 1958 by the local industrialist Louis Breguet for military usage (Cochard 2016), is one of the most valuable aircraft in the collection: only four were built in 1959 due to drastic budget cuts by the French government. After its last flight in 1974, this aircraft was stored outside at the Evreux air base (Normandy, France). It was transported after partial dismantlement from Evreux to Toulouse by truck and was added to the collection of the Ailes Anciennes Toulouse association in 1984, since when it has been stored uncovered outdoors and subject to ongoing

renovation. The aircraft has been suffering from severe corrosion for several decades. Figures 1c and 1d show an example of a corroded stringer made of aluminium alloy that had to be removed.

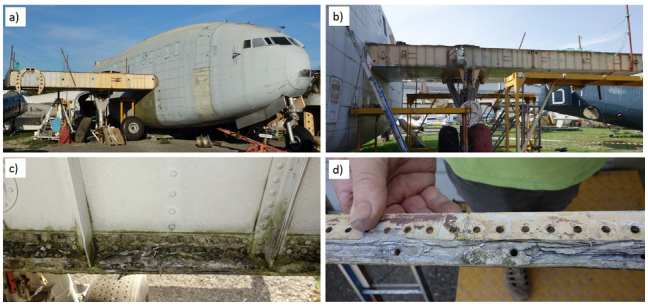


Figure 1. Photographs of (a) the Breguet 765; (b) the trailing edge; and (c) and (d) a corroded stringer on the centre wing section that was removed by a member of the association

After discussing the issue of corrosion with members of the association, it was decided to focus the study on parts made of aluminium alloy in order to understand the specific corrosion involved and to propose a diagnosis. Two lines of action were pursued: in-situ observation of the evolution of the corrosion and the physicochemical analysis of the collected parts.

Corrosion evolution was observed and documented on various parts of the aircraft by taking pictures every six months over a period of two years. For material analysis, some parts were collected after being removed by members of the association. These parts suffered from corrosion and needed to be replaced. The first step was to document these pieces thoroughly, i.e. their functional role (structural, cladding, etc.), their exact location on the aircraft and environmental conditions. In the second step, a full metallographic study was carried out on selected representative parts: stringers, plates, rivets (Cochard et al. 2017, Brunet et al. 2019). It consisted, for the bulk, of determining the elemental composition, the microstructure and the precipitation by optical and electronic microscopy techniques at different scales. For this, samples were embedded in epoxy resin and mechanically polished. On the cross section, the bulk metal, the different protective coatings employed and the corrosion features could be observed. Scanning electron microscopy was carried out with a JEOL JSM 6460 LV operated at 20 kV and equipped with an Oxford INCA PentaFETx3 energy dispersive x-ray spectrometer (SEM-EDS). The use of destructive methods was possible because the removed parts were numerous and were otherwise disposed of by the association members. The results of the metallographic study are summarised below. This article focuses on the alterations and diagnosis.

Results

General observations on the alterations and on the environment

A first observation of the aircraft revealed that corrosion had affected the stringers in general, whereas the skin (the outer surface of an aircraft's fuselage and wings) was better conserved (Figure 2a).

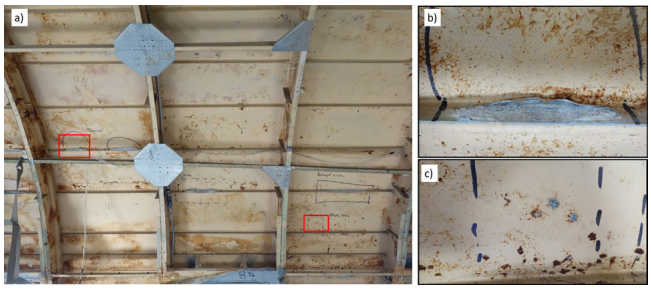


Figure 2. Photographs of (a) the interior; (b) exfoliation corrosion on stringers; and (c) pitting corrosion on fuselage plates

Stringers are part of the primary structure of an aircraft. Their role is to stiffen the fuselage, wings, empennage and central section, etc. and they are generally flat or possess L-shaped profiles riveted to the plates between the fuselage frames. They are visible in the interior of the Breguet 765 as the protection plates had been removed for renovation purposes.

Environmental conditions inside the plane are quite unstable as it has never been sealed since it was stored in Evreux or in Toulouse and the humidity rates can easily be high. On the outside, rain can reach unprotected parts and water can remain stagnant in gaps. Although all parts are covered by a protective coating, such as primer (greenish) and paints (yellow/beige), corrosion has developed locally.

For stringers, severe exfoliation is sometimes observed. This corrosion causes the aluminium alloy to delaminate and eventually turn into powder. For plates, whether structural (skin of the wings, fuselage) or non-structural (shields, cladding), corrosion in the form of pits is generally observed.

Figure 3 shows the evolution of the corrosion on particular zones of the aircraft interior: a stringer (Figure 2c) and a plate (Figure 2d).

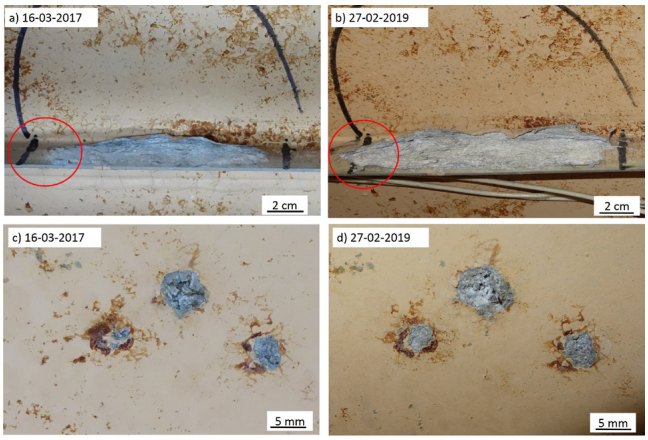


Figure 3. Photographs of (a) exfoliating corrosion on stringers (interior) and (b) pitting corrosion on the fuselage (interior) on March 2017 and after two years (b and d)

There is a clear sign of the development of corrosion on the stringers (about 1 cm per year), whereas for the plates the evolution is not so clear: pit diameters remain constant but with more corrosion products. According to these observations, stringers seem to have a lower resistance to corrosion than plates. To understand and appreciate the extent of these specific alterations, several stringers and plates were collected and studied.

Material analysis: Bulk alloy

In the first step, analysis by SEM-EDS on polished samples provided identification of the bulk alloy of the parts collected on the Breguet 765. The elemental composition for each alloy is given in Table 1. All collected parts are found to be made of duralumin, a family of alloys containing copper (3.5–5.5 wt%), magnesium (0.4–1.5 wt%) and manganese (0.5–0.7 wt%). Over time, these age-hardening alloys, with their excellent properties (light weight and high strength, in particular), became the material of choice for aircraft construction (Starke Jr and Staley 1996). In France, an alphanumeric denomination (A for aluminium, U for copper and G for magnesium followed by the nominal content in wt%) was adopted in the early 1940s (Lebouteux 1956) and this denomination was followed by the aeronautic standard AIR 3350/C of 1957 (AIR 3350/C 1957). The alloys used in the Breguet 765 were thus identified according to this standard. The collected stringers are made of A-U4G1. As for the plates, A-U4G was used for the non-structural parts whereas A-U4G1 was used for the parts in the primary structure. Here, the choice of alloy was governed by the mechanical properties resulting from its composition and thermomechanical treatments. The ultimate strength, yield strength and hardness of A-U4G1 is significantly higher than A-U4G (AIR 3350/C 1957) which justifies its use for the primary structure of the aircraft.

Table 1. Elemental composition (wt%) of plates and stringers analysed by SEM-EDS vs reference alloy composition provided in AIR 3350/C (1957)

	Elements in wt%	Al	Cu	Mg	Mn	Si	Fe
Analyses	Structural plates	Base	4.8–4.9	1.3–1.5	0.5–0.8	0.1–0.2	0.2–0.3
	Non-structural plates	Base	4.3	0.6-0.8	0.6-0.8	0.6-0.7	0.3–0.5
	Stringers	Base	4.9–5.2	1.5–1.6	0.8–0.9	0.1–0.2	0.2
Ref.	A-U4G	Base	4	0.7	0.5	0.5	0.5 max
	A-U4G1	Base	4.25	1.5	0.7	0.4 max	0.5 max

In the second step, the microstructure of the different alloys was studied. Figure 4 shows representative SEM images in backscatter mode for a plate made of A-U4G (Figure 4a) and a stringer made of A-U4G1 (Figure 4b). Coarse intermetallic particles analysed by EDS were identified as S-Al_2CuMg, AlCuMgSi, θ-Al_2Cu and particles containing Al, Cu, Fe, Mn and Si with varying stoichiometry. It should be noted that in A-U4G alloys, where the magnesium content is lower, the S-Al_2CuMg phase is absent. Coarse intermetallic particles are deleterious to the macroscopic properties, potentially causing cracks and corrosion (Hughes et al. 2011, DeRose et al. 2013). It is therefore important to document them in terms of size and density to understand the alteration in old alloys. In stringers, particles are smaller and more numerous than in plates (see Table 2 for statistics).

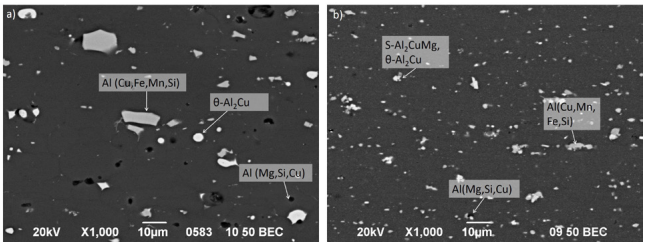


Figure 4. SEM images (backscatter electron mode) of collected pieces: (a) plate made of A-U4G; (b) stringer made of A-U4G1

Table 2. Average density, size and area of particles as a fraction of the total alloy surface for a representative plate and stringer

	Density (/mm²)	Particle size (µm²)	Area fraction
Plate (A-U4G)	12000	1.9 ± 4.2	2.3%
Stringer (A-U4G1)	31200	1 ± 1.7	3.1 %

After etching in Keller's solution (HF 1 mL, HNO_3 2.5 mL, HCl 1.5 mL in 95 mL demineralised water), metallic grains were revealed.

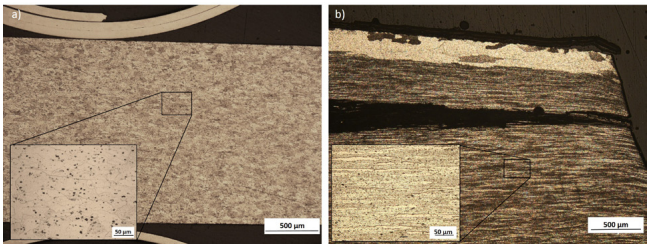


Figure 5. Optical microscope images after Keller's reagent etching: (a) plate; (b) stringer at 5× and 50×

The microstructure observed in the different parts can partially reveal the fabrication process. Plates have equiaxed grains (Figure 5a) typically obtained after successive rolling passes and heat treatments leading to recrystallisation, whereas stringers exhibit a highly oriented fibrous structure in the bulk and large grains on parts near the surface up to a depth of a couple of hundred microns (Figure 5b). This peculiar microstructure is linked to the manufacturing process where extruding generates severe plastic deformation giving rise to a very fine and oriented texture – the *presseffekt* (Herenguel and Scheidecker 1954, Develay 1997) – to create higher mechanical resistance. In subsequent heat treatments, the microstructure undergoes an inhomogeneous recrystallisation with the formation of large grains on the cortex, as observed here. These large grains induce a reduction in mechanical properties and also influence resistance to corrosion.

In terms of protective coatings, and depending on whether the part was for internal or external use, it was found that anodisation and/or a primer was applied underneath several layers of paint. The full characterisation of the parts can be found in a previously published work (Brunet et al. 2019).

Alterations and diagnosis

As mentioned above, two types of alterations (pitting and exfoliation) were identified macroscopically on the parts collected from the Breguet aircraft. These forms of corrosion are highly representative of outdoor corrosion of aluminium alloys (De Damborenea and Conde 1995, De La Fuente et al. 2007). Figure 6 shows pictures of the corrosion, via a top view and in cross section, on plates (Figures 6a and 6b) and on stringers (Figures 6c and 6d).

Inside pits, white and blue corrosion products were observed. They are known to be hydrated variants of aluminium oxides and hydroxides (Degrigny 1991), as well as aluminium sulfates (Graedel 1989). The blue colour comes from the copper ions released by the alloy. When observing these corrosion features on cross sections in larger scale with SEM (Figure 7), it is clear that intergranular corrosion has developed on both the plates and stringers. On the plates, the intergranular corrosion is coupled with evolving pitting in the crevices (Figure 6b), while on the stringers the intergranular corrosion further develops during exfoliation (Figure 6d).

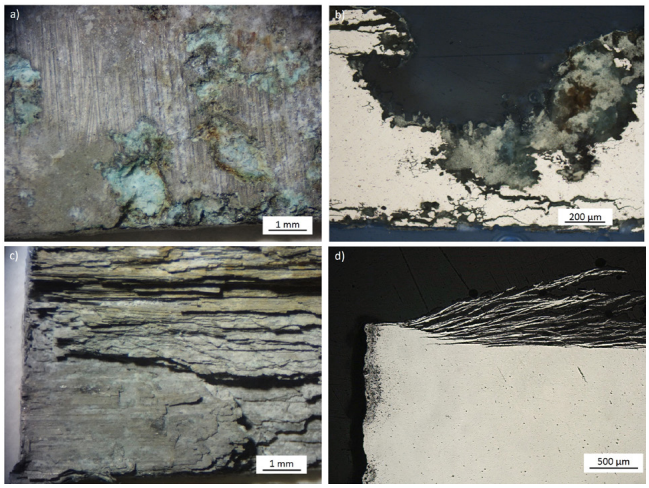


Figure 6. OM images on plates: (a) top view; (b) cross section showing pitting corrosion; and on stringers: (c) top view, (d) cross section showing intergranular corrosion leading to exfoliation

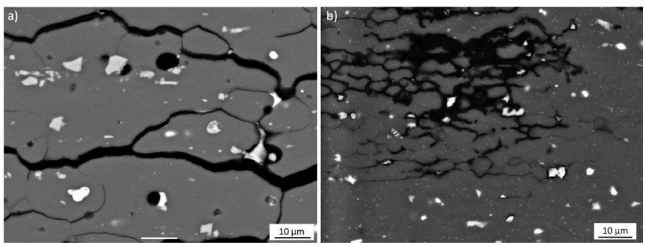


Figure 7. SEM images (backscatter electron mode) of corroded parts: (a) plate made of A-U4G; (b) stringer made of A-U4G1

The observed forms of corrosion (pitting, intergranular, exfoliation) can be explained by environmental and intrinsic factors (the composition and microstructure of the alloy). According to the literature, when exposed to air, an amorphous oxide film (Al_2O_3) is formed instantaneously on the aluminium surface. Upon prolonged exposure to humidity, the film grows and transforms into hydroxides (boehmite, bayerite, nordstrandite, etc.) (Graedel 1989). The resulting film is highly porous. In atmospheres that contain corrosive salts, humidity and constituents such as sulfur compounds and chlorides are absorbed and cause the film to rupture. By reaching the bulk metal, these contaminants may generate pitting corrosion (De la Fuente et al. 2007).

In duralumin alloys, different types of intermetallic particles are present (as shown in Figure 4) with different dissolution potentials (Hughes et al. 2011). Copper-rich particles (θ-Al_2Cu) and iron-rich particles (Al-Cu-Fe-Mn-Si) are cathodic compared to the solid solution, whereas Mg_2Si and S-Al_2CuMg particles are anodic. In the presence of aqueous electrolytes, micro-galvanic coupling occurs between these particles and the matrix. This can occur readily after the protective coating is broken allowing humidity to penetrate. Anodic particles dissolve preferentially. Cathodic particles, on the other hand, deplete copper concentration in the surrounding matrix at microscale. This copper-depleted zone is more anodic compared to the matrix and oxidises easily, with the matrix dissolving preferentially. The case of S-Al_2CuMg particles is specific: preferential dissolution of magnesium and aluminium creates a copper-rich zone around the particle. This zone, more cathodic than the particle, stimulates secondary pitting (Guillaumin and Mankowski 1998).

All of these phenomena are localised corrosion processes originating from surface heterogeneities inducing either pitting or intergranular corrosion. Intergranular corrosion develops specifically when grain boundary regions are preferentially attacked, due to the presence of intermetallic particles at grain boundaries or the presence of a precipitate-free zone, as well as other factors such as misorientation (Hughes et al. 2011).

In the case of the parts from the Breguet 765, intermetallic particles are more numerous and denser on stringers than on plates (Figure 7), which partly explains why corrosion is an issue on stringers. To explain why the intergranular corrosion transforms into exfoliation on stringers, an important factor is the microstructure linked to the manufacturing process and heat treatments. On plates, exfoliation does not occur because of the homogeneous microstructure obtained after recrystallisation annealing. On stringers, due to the particular oriented and fibrous microstructure mentioned above, the intergranular corrosion develops easily into exfoliation due to the growth of corrosion products which force metal to move away from the body of the material.

To summarise, intergranular corrosion begins in the intermetallic precipitates present in the alloys as well as in the grain microstructure. It is a self-generating process as long as humidity can penetrate and thus very difficult to stop. The nature of the alloy is important: A-U4G1 containing S-Al_2CuMg particles would be expected to be less resistant to corrosion; however, similar corrosion features could be observed on different alloys of the same family, i.e. A-U4G and A-U4G1, which leads to the conclusion that thermomechanical treatment during fabrication was, in this case, a determining factor for the corrosion mechanism.

Discussion

Corrosion affects aluminium alloys differently depending on many factors: intrinsic factors (such as chemical composition and thermomechanical treatments during fabrication) and extrinsic factors (such as protective coating efficiency, mechanical stress during usage and environmental conditions). Due to these specificities of aluminium alloys, it remains difficult, at first sight, to develop a global conservation strategy. Obtaining as complete a view as possible of the materiality of the cultural heritage object, via sampling and/or archival research, is therefore a particularly important step to evaluate the potential risks of alteration. In fact, when considering the long-term preservation of old aircraft exposed to the elements, decisions on conservation protocols are potentially easier to make if knowledge on the resistance to corrosion of specific aluminium alloys is acquired upstream. In the case of the Breguet 765, thanks to the study on various collected parts, a better understanding of factors which caused corrosion was achieved. Following this, several preventive conservation measures were transmitted to the association members. In particular stringers, because of their low resistance to corrosion, have to be closely controlled. More generally, for aircraft kept outside, humidity/rain/pollution penetrates easily through damaged coatings initiating corrosion. Original protective coatings must therefore be conserved as far as possible.

When corrosion is detected, the methodology currently used by the association's members is the following: polishing with a non-metallic brush until corrosion products are completely removed, degreasing of the area and immediate application of an epoxy-base primer (used in aircraft industry maintenance). This method is not one hundred percent efficient as corrosion can start again. When the corrosion is more severe, such as exfoliation, the association's members have no choice but to change the affected parts, as this type of corrosion is difficult to stop. For this particular aircraft, it means changing a lot of parts, which is far from ideal.

Right now, adapted methods need to be defined upstream by the conservation-restoration community, together with renovation organisations, to conserve aluminium alloys in cultural heritage artefacts exposed to outdoor conditions. In particular, a methodical process should be undertaken to ensure aluminium alloys are exposed to corrosion conditions as little as possible.

Conclusion

This study highlights the interest in developing a major strategy when investigating complex industrial and cultural heritage. The relationship between the role of the parts (structural or non-structural) and the choice of materials was revealed through material analysis coupled with researching the constructor's technical documents. It was found that A-U4G and A-U4G1 were employed depending on the desired mechanical characteristics. Corrosion on the plates and stringers was then investigated and it was observed that the exfoliation on the plates is closely related to the microstructure created during the fabrication process. It was therefore shown that identifying the chemical nature and the microstructure of the alloys was a necessary step to a better understanding of the alterations involved.

Conservation and restoration practices on ancient aircraft remain complex due to the size of the aircraft and the high number of alloy types. However, similar aluminium alloys can be found in many aircraft from different periods. Knowing in advance what the potential risks are for one part or another due to the chemical nature, fabrication process or environmental conditions is a useful source of information to be filed in a database and should help actors in the conservation field facing similar problems in the future.

Acknowledgements

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Authors

Magali Brunet is a research scientist in materials science at CNRS (Centre national de la recherche scientifique) who has worked at CEMES (Centre d'Élaboration de Matériaux et d'Etudes Structurales) on the Cultural and Industrial Heritage Materials team since 2015. She studies alterations to old materials, in particular aluminium alloys, using physicochemical analysis techniques. She holds a PhD in Microelectronics Engineering from Cork University (2003) and a master's degree in Conservation and Restoration of Cultural Heritage from the University of Paris 1 Panthéon-Sorbonne (2015).

Luc Robbiola is a research engineer in cultural materials science at CNRS. He holds a PhD in Metallurgy (1990) and a master's degree in Conservation and Restoration of Cultural Heritage from the University of Paris 1 Panthéon-Sorbonne (1985). He presently works at Toulouse University in the TRACES (Travaux et Recherches Archéologiques sur les Cultures, les Espaces et les Sociétés) laboratory for the new ArchéoScience platform.

Philippe Sciau is a research scientist in materials science at CNRS, working at CEMES in the Cultural and Industrial Heritage Materials team.

Monique Drieux-Daguerre has been the head of Materia Viva since 2001, a conservation laboratory in Toulouse specialising in the preservation of archaeological and historical heritage, in particular metals. She has a master's in Archaeology and Art History and a master's in Conservation of Cultural Heritage from the University of Paris 1 Panthéon-Sorbonne.