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First step in the PROCRAFT Project on WWII Aircraft Heritage: Investigation and Conservation of the Aluminium Alloys

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Abstract

The conservation of excavated wrecks or abandoned aircraft is of cultural and historical interest. A first step in understanding the challenges posed by this type of cultural heritage and in finding solutions for its conservation is to document the constituent materials and their subsequent alterations. In the project PROCRAFT, aircraft wrecks from six nations involved in WWII were collected and then studied. Analysis of the elemental composition together with archival research allowed identification of the wrought aluminium alloys used in the non-structural and structural parts of the aircraft. Three manufacturing processes were recognised: rolling, extrusion and forging. The corrosion protection treatments applied during manufacturing of the aircraft parts were also examined, which revealed cladding with a thin aluminium foil, anodisation or the application of primer/paint. Based on typical examples of the alterations that occurred in the metal components, we demonstrate the importance of this original protection against the aggressiveness of the environment.

Keywords

aircraft heritage, aluminium alloys, Al cladding, protective coatings

Introduction

Although WWII is often considered the golden age of military aviation, battles in the air resulted in enormous human and material losses, with the latter including a large number of wrecks on European soil and in the sea. Volunteers and associations have long been engaged in recovering the wrecks, but despite the undeniable historical and emotional value of WWII aircraft for Europeans, only recently have these heritage objects come to the attention of archaeologists and conservators. Nonetheless, they are still rarely exhibited in museums.

The challenges in the conservation and protection of aircraft heritage include the documentation of constituent historical materials and their alterations as well as the need for innovative approaches to the development of protective coatings and to the monitoring and control of atmospheric conditions in storage and display areas. These challenges are addressed in project PROCRAFT (PROtection and conservation of heritage airCRAFT)1], a joint programming initiative on cultural heritage. The project also aims at connecting the multiple actors in the operational chain, and specifically those in France, Italy and the Czech Republic, from the recovery to the exhibition stage.

The present study was based on the work carried out by several associations (Aérocherche, Aérothèque, Ailes Anciennes Toulouse, Aéroscope and ABSA 39-45 in France; Volandia and Air Club & Fun in Italy) that excavated or collected wrecks from various environments (terrestrial ground, sea, lakes), mainly in France and Italy, and gathered information/testimonies related to the crashes. The first task of the project was to identify and record a significant group of WWII aircraft/wrecks, most of which are bombers and fighters from Germany, France, Italy, the USA, the UK and the USSR that crashed during military operations between 1939 and 1945. Other aircraft, including civil planes abandoned after the end of their lifetime and recovered years later (such as the Dewoitine D.338) dating from the same historical period, were considered as well.

Documentation of the artefacts, parts of wrecks or full aircraft, and their constituent materials is an important part of understanding aeronautical heritage, especially since archival data are difficult to recover. Moreover, recording the condition of the artefacts (their alteration) will provide insights into the main parameters driving corrosion. This knowledge will be used by PROCRAFT to select restoration treatments, determine the appropriate protective coating for these materials and, eventually, develop the appropriate preventive conservation procedures and facilities (large storage hangar, outdoor storage).

This article focusses on the first task of the PROCRAFT project, which was to obtain detailed information on a wide set of WWII aircraft, including the identification of wrought aluminium alloys, the principal materials used in the construction of aircraft, and their anti-corrosion protection. A summary of the conservation state of the aircraft is provided and the relations between the alloy manufacturing, the environment and the extent and morphology of the corrosion are discussed.

Methodology and experimental setup

A methodology was developed to uniformly record information on each aircraft/wreck. Briefly, in a first step information is collected on the historical context, the circumstances of the crash or the abandonment of the aircraft, details about its excavation or recovery, the global condition of the aircraft (sometimes less than 1% of the whole aircraft is recovered) and the availability of any archives linked to the aircraft. All original documents are clearly very important to correctly classifying the aircraft, whether historically or technically.

In a second step, the constituent materials (aluminium alloys and protective coatings) are identified and their conservation state is assessed. Macro- to micro-scale observations of the samples coupled with elemental and structural analyses are performed to extract precise information on the elemental composition and microstructure of the alloys as well as on the

nature and composition of the original protective coatings. Corrosion features are also examined.

For this study, representative samples were prepared by cutting the aircraft parts along three spatial directions: rolling or longitudinal (L), short transverse (i.e. thickness, ST) and long transverse (LT), defining the main metallurgical planes: rolling (L, LT), transverse (LT, ST) and normal (L, ST), as shown in the insert of Figure 1. The sections were then prepared, embedded in epoxy resin, mechanically polished down to 2400 SiC paper grade and then polished on diamond paste cloths down to 1 μm particle size to obtain a mirror-like finish. The elemental compositions of the alloys were determined using a scanning electron microscope (SEM) (LaB₆ Zeiss EVO 25) operating at 20 keV (1 nA) equipped with a Bruker XFLash energy dispersive X-ray spectroscopy (EDS) detector. Three measurements of 5 million counts on $\sim 0.2 \text{ mm}^2$ areas were averaged. Quantitative determination was carried out with a Quantax system (Bruker Esprit 2.1 software), applying the phi-rho-z method. The results were normalised to 100 wt% after carbon deconvolution. Images in backscattering electron (BE) mode completed with EDS maps were acquired for the detection of protective coatings and the observation of corrosion features.

Results and discussion

Identification of alloys and their anti-corrosion protection

The 34 aircraft obtained thus far are from Germany (6), France (7), Italy (5), USA (7), UK (2) and USSR (1). Five artefacts have yet to be attributed to a specific aircraft and thus to a country. As invasive analyses could not be performed on some aircraft, 16 artefacts for which sampling could be performed are presented below.

Wrought aluminium alloys are used in three manufacturing processes (Davis and Semiatin 1989): rolled products (plates or sheets, mainly fuselage skin), extruded products (stiffeners, stringers, both with a structural role; Alderliesten 2018) and forged products (parts with complex shapes). In addition, some stiffeners riveted to plates are fabricated by rolling and folding.

Identification of alloys

Since corrosion is directly linked to microalloying elements and microstructure, identification of the alloy type in relation to the manufacturing processes is critical for establishing a diagnosis and, subsequently, conservation protocols.

In most of the collected and analysed samples (Table 1), the wrought alloys were exclusively Al-Cu-Mg (Si), corresponding to the Duralumin family, nowadays referred to as Al alloys of the 2000 series. The nominal composition of these alloys is Cu (3–5 wt%), Mn (0.4–1.5 wt%), Mg (0.5–1.7 wt%) and Si (0.5 wt%). Si is either not controlled or it is added in small quantities whereas Fe, also present in the alloy composition, is always an impurity. Trace amounts of other elements ($< 0.1 \text{ wt}\%$) may occur as well: Zn, Ti, Ni, Pb.

As reported in Table 1, two specific sub-families of alloys can be classified. Their denomination differs according to country (Ouissi et al. 2019, Ouissi 2020):

- Duralumin, with a Mg content < 1 wt%: the forerunner of the modern 2017A alloy, called Duralumin or A-U4G in France (Chevigny 1954), AlCuMg1 or 3115 in Germany (Böhle 1956), Hiduminium DU Brand in the UK (High Duty Alloys 1948) and 17S in the USA (*ALCOA aluminum and its alloys* 1935);
- Super Duralumin, with a Mg content of 1–1.5 wt%: the forerunner of 2024 alloy, called Duralumin FR or A-U4G1 in France, AlCuMg2 or 3125 in Germany, Hiduminium 72 in the UK and 24S in the USA. This alloy has a high yield, a high ultimate strength and a high degree of hardness.

For German aircraft, both Duralumin (AlCuMg1) and Super Duralumin (AlCuMg2) were used in the manufacture of rolled and extruded products. The choice of alloy for the different parts of the aircraft was left to the manufacturers. It should be noted that on some parts, e.g. the stringer of DO 217 and plate 2 of the Junkers 88, the measured Mg content was at the border of Duralumin and Super Duralumin. In these cases, the alloy was classified according to the content of other elements, Mn and Si in particular.

Duralumin (low Mg rate < 1 wt%) was used in most French aircraft for structural and non-structural parts. However, contemporary studies have shown that Super Duralumin was used in France only after WWII (Guillemin 1946). For example, the Espadon, an aircraft from 1948, was fabricated with Duralumin, which was selected for both the structural and non-structural parts (stiffeners).

In American aircraft, Super Duralumin (24S alloy) was used for non-structural (skin) and structural parts. The alloy was employed in aeronautical construction already in 1937, first in the DC-3 and then more widely (*ALCOA* 1935).

Among British and Italian aircraft, only Duralumin has been identified so far in the collected parts.

The two forged products in the collection are propeller blades, one from a Lockheed P38 and the other from an unidentified aircraft. The P38 alloy, which does not contain any Mg, is a 25S alloy. As noted in ALCOA's archives (*ALCOA* 1935), the 25S was specifically developed for forged products, with its advantage consisting of a higher resistance to high temperatures. The alloy of the blade from the non-identified aircraft is Duralumin.

Table 1. Elemental composition (wt%) of wrought aluminium alloys and the protective coatings of aircraft from five countries

| | Constructor / Aircraft (year of prod.) | Product /Manufacturing /Thickness (mm) | Elemental composition (wt%) | | | | | | Identified alloys | Protectio n*/ Thickness (µm) |
|---|--|--|-----------------------------|------|------|------|------|------------------|----------------------|------------------------------|
| | | | Al | Cu | Mg | Mn | Fe | Si | | |
| Germany | Dornier/Do 217 (1943) | Sheet / Rolled / 1 | 93.65 | 4.04 | 0.83 | 0.50 | 0.40 | 0.35 | AlCuMg1 | C / 50 |
| | | Stringer / Extruded / 3.5-5 | 92.71 | 4.20 | 1.14 | 0.81 | 0.33 | 0.51 | AlCuMg2 | ND |
| | Heinkel /He 111 (1937) | Stringer / Extruded / 2 | 93.21 | 4.29 | 0.61 | 0.75 | 0.34 | 0.46 | AlCuMg1 | O |
| | Heinkel / He 177 (1943) | Plate / Rolled / 1 -1.4 | 93.39 | 4.43 | 0.71 | 0.55 | 0.29 | 0.41 | AlCuMg1 | C / 50 |
| | Messerschmitt/B f 109 (1944) | Plate / Rolled / 1.1 -1.2 | 93.59 | 4.13 | 1.52 | 0.49 | 0.15 | 0.02 | AlCuMg2 | C/ 50 |
| | Junkers / Ju 88 (1943) | Engine plate 1/ Rolled / 1.1 | 93.21 | 4.64 | 1.34 | 0.45 | 0.15 | 0.07 | AlCuMg2 | C / 75 |
| | | Engine plate 2/ Rolled / 1.5 | 93.67 | 4.15 | 0.97 | 0.39 | 0.24 | 0.40 | AlCuMg1 | C / 75 |
| Stiffener/ Rolled and folded / 0.8 | | 92.84 | 4.75 | 0.80 | 0.51 | 0.32 | 0.59 | AlCuMg1 | A | |
| France | Dewoitine/D.520 (1940) | Plate / Rolled / 0.7-2 | 93.20 | 4.35 | 0.50 | 0.56 | 0.31 | 0.46 | Duralumin | O |
| | Dewoitine / D.338 (1937) | Stiffener / Extruded / 2.5 | 94.05 | 3.58 | 0.59 | 0.52 | 0.34 | 0.64 | Duralumin | A |
| | | Skin / Rolled / 0.5 | 93.13 | 4.45 | 0.79 | 0.62 | 0.31 | 0.50 | Duralumin | C |
| | SNCASO/ Espadon (1948) | Skin / Rolled / 2.0 | 93.68 | 4.32 | 0.65 | 0.47 | 0.36 | 0.34 | Duralumin | C |
| Latécoère/ Laté 298 (1940) | Plate / Rolled / 1.5 | 93.69 | 4.16 | 0.69 | 0.58 | 0.24 | 0.56 | Duralumin | C / 95 | |
| UK | Supermarine / Spitfire (1942) | Plate / Rolled / 1 – 1.2 | 93.26 | 4.19 | 0.94 | 0.65 | 0.43 | 0.49 | Hidu DU Brand | ND |
| | | Stiffener / Rolled and folded / 1.8 | 94.06 | 3.68 | 0.91 | 0.63 | 0.38 | 0.28 | Hidu DU Brand | ND |
| USA | Republic Aviation / P47D Thunder. (1943) | Plate / Rolled / 1 | 92.72 | 4.78 | 1.45 | 0.54 | 0.27 | 0.15 | 24S/ | C / 50 |
| | | Stiffener / Extruded / 1 | 93.15 | 4.33 | 1.32 | 0.55 | 0.31 | 0.18 | 24S | ND |
| | Lockheed/P-38 Lightning (1943) | Skin / Rolled / 1 | 91.63 | 5.44 | 1.55 | 0.57 | 0.39 | 0.42 | 24S | C / 30 |
| | | Stiffener / Extruded / 1 | 91.63 | 5.64 | 1.51 | 0.62 | 0.31 | 0.30 | 24S | A |
| Lockheed / P38 (<1944) | Blade / Forged / 2-112 | 93.58 | 4.57 | 0.05 | 0.70 | 0.44 | 0.53 | 25S | A | |
| Italy | IMAM RO37 (1936) | Plate / Rolled / 0.7 | 94.35 | 3.86 | 0.53 | 0.55 | 0.42 | 0.21 | Duralumin | ND |
| | Macchi /MC202 (1942) | Sheet / Rolled / 0.9 | 91.87 | 4.64 | 0.94 | 1.43 | 0.39 | 0.66 | Duralumin | ND |
| | Unknown | Blade / Forged / 3-66 | 93.70 | 4.05 | 0.59 | 0.64 | 0.40 | 0.24 | Duralumin | A |

* C = Al cladding ; A = anodisation; O = organic (primer/paint) ; ND = not determined

Identification of the protection type

The corrosion of aluminium alloys was an early concern for aluminium manufacturers. Although paint was initially applied mainly as colouring/camouflage, it also ensured corrosion protection. Primers with anti-corrosion pigments (chromates) were applied underneath. Other types of protection in the 1920s included anodisation. However, due to cost issues and difficulties in treating large areas with this process, it was replaced in the late 1920s by a method in which the alloy was clad between two thin sheets of pure Al, called Alclad in the USA (Dix 1927) and Vedal in France (Pubellier 1929).

Most of the recovered WWII aircraft in the collection (Table 1) were originally painted but the paint has been retained on only a few of them. In cases of severe corrosion, the original protection is missing and cannot be inferred (ND).

Nonetheless, Al cladding was largely found on rolled products, especially fuselage skin and plates. Figure 1 shows an example of an Al-cladded plate in cross-section. For plates of ~1 mm thickness, the cladding layer is typically between 50 and 100 µm. Al cladding was systematically employed in German and American aircraft parts, but not always in French aircraft parts. Several plates of the Dewoitine D.520 (1940) had not been cladded whereas plates of the D.338, an earlier aircraft (1937) from the same manufacturer, had Vedal. It may have been the case that corrosion protection was chosen according to the expected durability of the aircraft. Thus, Vedal was used to protect civil aircraft (such as D.338), expected to be in use for many years, while short-life fighters (such as D.520) had no cladding at all. Among the plates recovered on British and Italian aircraft, no cladding was found but they were also strongly altered and difficult to assess.

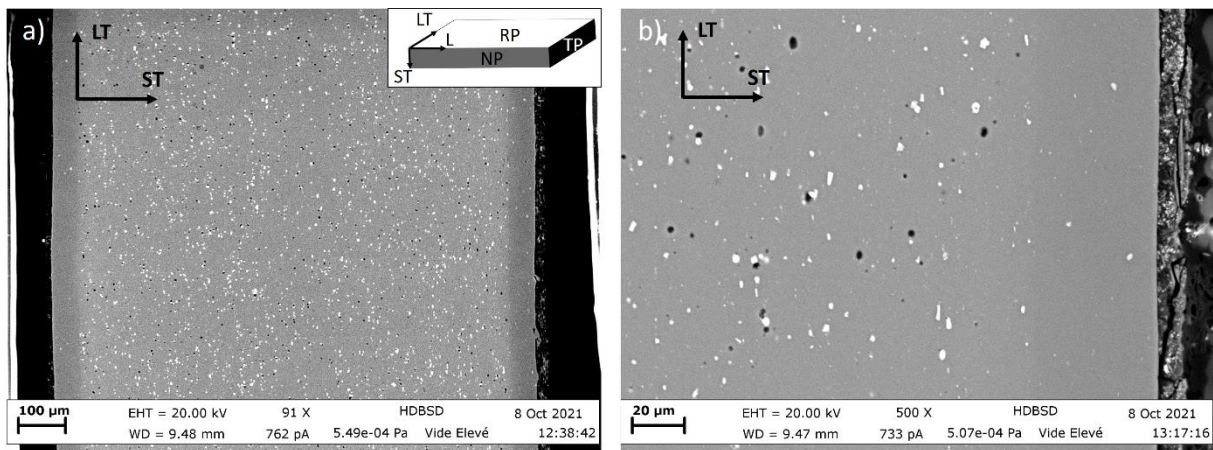


Figure 1. SEM-BE images of a plate from a Messerschmitt Bf109, evidencing Al cladding: (a) full view, (b) close-up view. Insert: main spatial directions and defined planes of the rolled products

Some of the extruded profiles and forged products (blades) had been anodised but the thin layer of aluminium oxide (few microns) is sometimes difficult to distinguish from a corrosion layer.

In summary, only a few of the aircraft parts had primer and paint as the sole protection against corrosion. Those samples evidence the early awareness of aircraft manufacturers about the low corrosion resistance of Duralumin.

General observation of the conservation state of the artefacts

Most the artefacts suffered from corrosion due to their long burial in the ground or sea or to their prolonged abandonment in the open air. Figure 2 shows representative artefacts and the typically encountered alterations. Generally, Al-cladded products were more robust to burial or environmental conditions. This was demonstrated by the Dornier 217 fuselage (Figure 2a), which was left for decades in a chasm in the Pyrenees. However, as shown for the Junkers 88 (Figure 2b), the remnants of which had been used on a farm as the roof of a poultry house, the loss of material provided observable evidence that the Al cladding was no longer effective. On extruded profiles exposed to atmospheric conditions such as those of the Dewoitine D.338 (Figure 2c), the anodisation and paints originally present had significantly degraded. Pitting and intergranular corrosion could have quickly led to exfoliation corrosion, as previously reported (Brunet et al. 2019). In forged products, once the protection is lost, intergranular corrosion occurs, as has been observed in other wrought products. On artefacts recovered from the sea (Figure 2d), corrosion can be severe and the corrosion products often develop a blue colouring (Rocca et al. 2021).

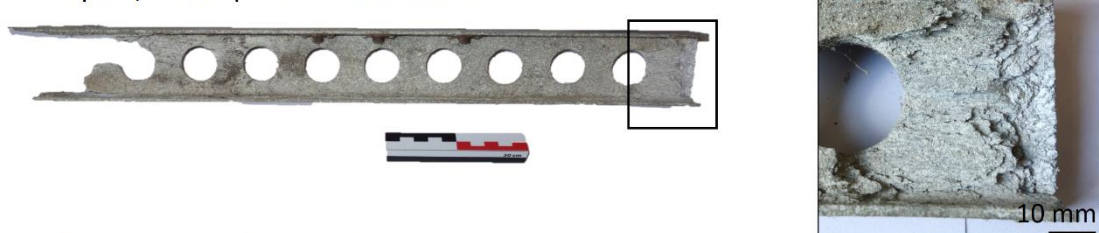
a) Rolled and extruded parts, atmospheric environment



b) Rolled parts, atmospheric environment



c) Extruded part, atmospheric environment



d) Forged part, sea environment



Figure 2. (left) Photographs of the artefacts. (right) Optical microscopy images of the alterations in the aircraft: (a) Dornier 217 fuselage (Al cladded), (b) Junkers 88 engine cowl (Al cladded), (c)

Dewoitine D338 stringer (anodised), (d) propeller blade recovered from the sea near Brest (Britany)

An understanding of the degradation processes requires the examination of corrosion in relation to the manufacturing process and the original means of protection. The environment and the history of the aircraft are key parameters that have to be considered. Depending on the burial environment and the cause of the crash (e.g. fire), the condition of the original corrosion protection, mostly Al cladding, can vary. A case study of the engine cowl of a Junkers 88 is presented below.

Correlation between the alloy manufacturing process, the environment, artefact history and corrosion forms

The Junkers 88, a bomber-fighter built in 1943, crashed in 1944 in southern France after being shot down by a British Mosquito. A fire was witnessed after the crash (Collaveri 2016). In 2010, a few fragments were excavated, including a fragment of an engine cowl. On the outside plate (plate 1, AlCuMg2 alloy), large concretions are present on the surface and only residues of paint remain. The inside plate (plate 2, AlCuMg1 alloy) shows material losses, especially on areas involved in the crash. Both plates have undergone macroscopic pitting corrosion, which can develop into exfoliation corrosion.

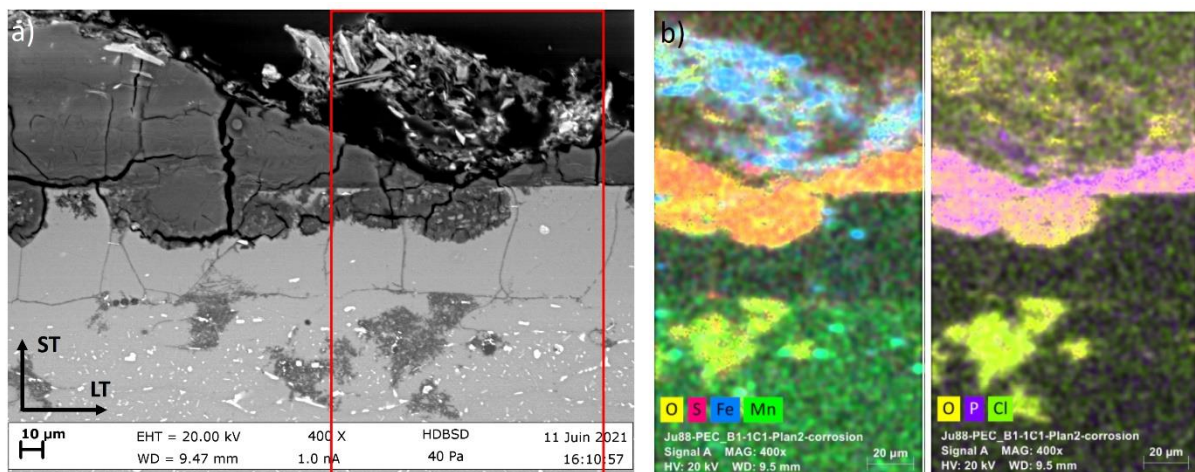


Figure 3. SEM-BE image and EDS maps of a cross-section (transverse plane) of the Junkers 88 (plate 1)

Figure 3 shows the SEM-BE images of the cladded Junkers 88 plate 1 in cross-section (transverse plane) and the corresponding EDS mapping. As shown by the latter (Figure 3b), the concretions (exogenous elements) include localised iron corrosion products. Under the concretions, thick aluminium corrosion products are present on the surface, while on the inner structure pits with elements such as sulfur and phosphorus are seen. Chlorine was also detected within the localised corrosion products. All of these elements indicate interactions with soil anions. Chlorides are the most aggressive species as they can induce the breakdown of the passive layer, leading to pit formation (localised corrosion).

An image of the pits within the Al cladding is provided in Figure 4, including evidence of the evolution of the corrosion attack inside the Al-cladded plate (Figure 4b). Localised corrosion developed laterally along the surface, within the cladding. The depth of the corrosion

corresponds to the end of copper diffusion – the result of the hot rolling process – inside the aluminium cladding. The resistance of Al cladding to corrosion was discussed in detail by Walton et al. (1953). Pure Al cladding provides good electrochemical protection, even in an aggressive natural environment. It also confers cathodic protection of the core alloy, such that corrosion will penetrate only as far as the core alloy or diffusion zone. Exposure of the Al cladding to the atmospheric environment (cycles of humidity) results in the formation of corrosion products such as aluminium hydroxides and/or sulfates. When present in large amounts, they induce cracks in the Al cladding layer, lifting it in some places and reaching the bulk alloy in others.

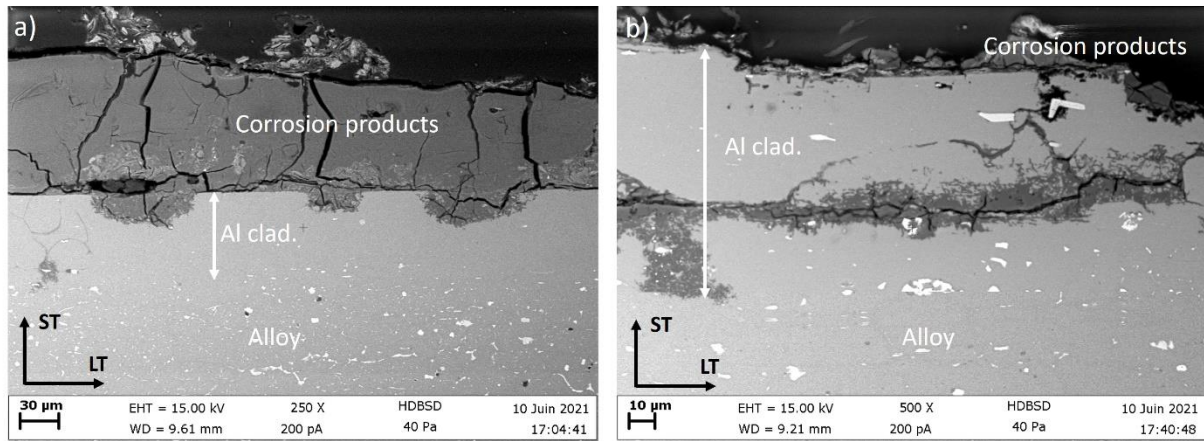


Figure 4. SEM-BE images of a cross-section (transverse plane) of the Junkers 88 (plate 1): (a) pitting corrosion starting on the Al cladding layer and (b) corrosion progressing within the Al-clad layer

In Figure 5, the corrosion has reached the bulk alloy, resulting in both intergranular and intragranular corrosion. The latter develops in the presence of humidity and is triggered by the intermetallic precipitates located mainly at the grain boundaries and by nano-size precipitates inside the grains (Figure 5b). These precipitates suggest exposure to heat, either while the aircraft was in use (proximity to the engine) or during the fire that occurred after the crash.

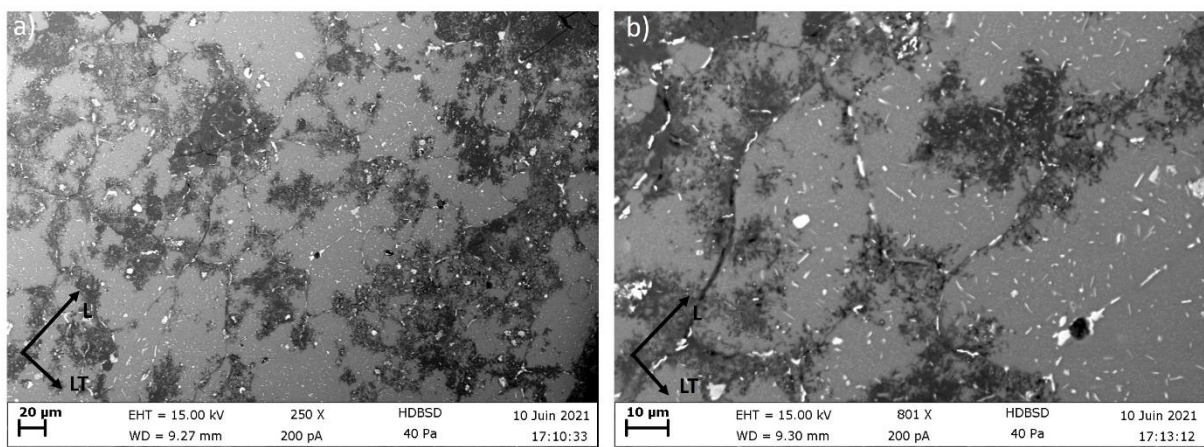


Figure 5. SEM-BE images of the Junkers 88 (plate 1, rolling plane): (a) general view, (b) close-up showing nano-size precipitates within the grains

The metallurgical observations demonstrate that an aggressive environment, including the presence of chlorine and sulfur, favours the degradation of the Al cladding layer. Once the bulk

alloy is reached, severe corrosion is initiated due to the intrinsic corrosion susceptibility of the alloy, accelerated by cycles of humidity.

The inside plate of the Junkers 88 (plate 2, AlCuMg1 alloy) also exhibits precipitation at the grain boundaries and the same corrosion patterns as seen in plate 1. Although it was expected that the alloy with the higher Mg content (plate 1, AlCuMg2) would be less resistant to corrosion, due to the increased formation of S-type precipitates (DeRose et al. 2013), this was not the main determinant of corrosion susceptibility in this case. Rather, the heat-induced precipitation at grain boundaries (present in both plates) played the larger role.

Complementary investigations are still needed, including transmission electron microscopy imaging to identify the nature of the nano-size precipitates and understand their role in the intragranular corrosion attack.

Conclusion

During WWII, different types of aluminium alloys were used by aircraft manufacturers. In most cases, Duralumin or Super Duralumin (with a higher proportion of Mg) was employed for both structural and non-structural parts of the aircraft. However, corrosion of these Al-Cu alloys was a well-known issue, which resulted in different corrosion protection strategies, most commonly cladding with pure Al for rolled products, anodisation or simply an anti-corrosion primer for some extruded products.

As a result, more than 70 years later, depending on the materials, in particular the original protective coating, and on the environment at the aircraft crash site, the alterations in the structural alloys are highly variable but often include pitting and exfoliation corrosion. This study focussed more specifically on the particular forms of corrosion that affect Al-cladded alloys. Aluminium-based alloys, even those that were protected, may further degrade after their removal from aggressive environments (marine or soil), as corrosion can continue due to exposure to cycles of humidity, which can promote exfoliation corrosion. Thus, future work in the PROCRAFT project will focus on the cleaning and stabilisation of representative artefacts. The low amount of chlorine elements detected within the corroded structure will allow for the refinement of current research areas within the project. In contrast to the dechlorination treatments used for iron or copper-based metals, restoration and stabilisation will require surface protection adapted to indoor or outdoor environmental conditions. Innovative protective coatings will be developed that take into account the surface conditions, i.e. alloy with or without Al cladding, the corroded metal and the painted surfaces. They will also be tailored to the surface state while complying with cultural heritage requirements regarding material compatibility and the preservation of the original surface aspect.

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Notes

1 <https://www.heritageresearch-hub.eu/project/procraft/>

References

Alderliesten, R. 2018. *Introduction to aerospace structures and materials*. Delft: Delft University of Technology. <https://doi.org/10.5074/T.2018.003>

ALCOA aluminum and its alloys. 1935. Pittsburgh, PA: Aluminum Company of America. https://archive.org/details/AlcoaAluminumAndItsAlloys_960 (accessed 14 March 2022).

Böhle, F. 1956. *Leichtmetalle*. Berlin, Heidelberg: Springer.

Brunet, M., L. Robbiola, P. Sciau, and M. Drieux-Daguerre. 2019. Preserving aviation heritage: The need for an approach based on material analysis. In *Metal 2019: Proceedings of the Interim Meeting of the ICOM-CC Metals Working Group, Neuchâtel, 2–6 September 2019*, eds. C. Chemello, L. Brambilla, and E. Joseph, 425–31. Paris: International Council of Museums–Committee for Conservation (ICOM-CC) and Haute Ecole Arc Conservation-restauration (HE-Arc CR).

Chevigny, R. 1954. L'aluminium et ses alliages. *Revue de l'Aluminium* 211: 175–79.

Collaveri, G. 2016. JU88. Aerocherche.fr website. <https://aerocherche.fr/index.php/articles-sur-les-avions/allemands/ju88> (accessed 14 March 2022).

Davis, J.R. and S.L. Semiatin. 1989. *ASM metals handbook, vol. 14: Forming and forging*. Materials Park, OH: AMS International.

DeRose, J.A., A. Balkowiec, J. Michalski, T. Suter, K.J. Kurzydowski, and P. Schmutz. 2013. Microscopic and macroscopic characterisation of an aerospace aluminium alloy (AA2024). In *Aluminium alloy corrosion of aircraft structures – Modelling and simulation*, eds. J.A. DeRose, T. Suter, T. Hack, and R.A. Adey, 23–38. Boston, MA: WIT Press.

Dix, E.H.J. 1927. *ALCLAD: A new corrosion resistant aluminum product*. Technical note no. 259. Washington DC: National Advisory Committee for Aeronautics.

Guillemin, J. 1946. L'évolution de la construction aéronautique de 1939–1946. *Revue de l'Aluminium et de ses applications* 127: 339–54.

High Duty Alloys. 1948. *HIDUMINIUM high duty alloys*. Slough: High Duty Alloys.

Ouissi, T., G. Collaveri, Ph. Sciau, J.M. Olivier, and M. Brunet. 2019. Comparison of aluminum alloys from aircraft of four nations involved in the WWII conflict using multiscale analyses and archival study. *Heritage* 2(4): 2784–801.

Ouissi, T. 2020. Evolution of light alloys in aeronautics: The case of Duralumin from its discovery to the end of WWII. *Nacelles. Past and Present of Aeronautics and Space* 8. <http://revues.univ-tlse2.fr/pum/nacelles/index.php?id=923> (accessed 14 March 2022).

Pubellier, M. 1929. L'emploi rationnel du Duralumin. *Revue de l'Aluminium et de ses applications* 34: 931–48.

Rocca, E., J. Tardelli, and F. Mirambet. 2021. 60 years' marine corrosion of aluminium alloy 24S (2024) from an historic aircraft wreck site: Implications for conservation. *Corrosion Engineering, Science and Technology* 56(3): 279–88.

Walton, C.J., D.O. Sprowls, and J.A. Nock. 1953. Resistance of aluminum alloys to weathering. *Corrosion* 9(10): 345–58.

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