Chapter 24 – MATERIALS REPLACEMENT FOR AGING AIRCRAFT

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24.1 INTRODUCTION

The criteria for the selection of materials for aircraft structure have evolved over the years. When the Wright brothers used the first cast aluminum engine block on the Flyer, the main drivers for material selection were weight and static strength. The main airframe materials were wood with fabric covering. Wood is a natural composite with long fibers of cellulose held together in a weaker matrix of lignin, which illustrates that using composite airframes is not a new idea. After development of precipitation hardening and the method to protect the surface of aluminum by cladding and anodizing, aluminum has been the primary material for airframe structures. Aluminum has been established in the aerospace industry, due to very high specific strength (strength/density), high toughness, ease of manufacture (major advantage being extrusion), long term performance, no low temperature brittle fracture, readily joinable by welding or mechanical riveting, and easily recyclable. Although pressure is increasing from composite fiber reinforced plastics, the latter three or four advantages seem to keep aluminum at the leading edge.

In the campaign for the position of "dominant material", aluminum producers are trying to reduce weight. Introduction of new designs, aluminum-lithium alloys, and rivet replacement with laser welding or Friction Stir Welding (FSW) can be cited as examples. However, the main thrust of polymer based composites producers is to develop low cost manufacturing methods. The dominance of aluminum received a serious blow when Boeing designed the 787 with almost 50% polymer based composite in its structure. Nevertheless, aluminum remains a highly attractive material from which to make aircraft and space vehicles. Its recycling and low weight advantages are essential considerations, as they are in the automotive industry.

Corrosion control in the aerospace industry has always been important, but is becoming more so with the ageing of the aircraft fleet. The new approach of "care free" structures suggests that optimized structures should be designed for minimum life cycle cost [1], which translates to crack-free long life, minimum corrosion and repair, and reduced inspection costs. Today combinations of low weight, fatigue resistance, durability, damage tolerance, reliability, manufacturability, maintainability, corrosion resistance, low manufacturing costs and low assembly costs are needed to satisfy the required operating costs and safety of aircraft. Winning products need to be light in weight as well as low in manufacturing costs and processing methods (e.g., friction stir welded fuselage panel using improved Al-Li alloys). In a case study by Airbus, wing ribs were manufactured using friction stir welding of 2050 alloy. The lower density and high modulus of the aluminum lithium alloys provided the weight saving, and low cost manufacturing was achieved by friction stir welding as opposed to machining [2],[3].

Since the earliest days of the aircraft industry, alloy selection has seen different methodologies such as safe life, fail safe, and damage tolerance (fail-safe + periodical inspection) designs. Aluminum alloys such as 7079 and 7075 were developed for high static strength, but failed to provide adequate toughness and corrosion resistance. Later, alloys such as 7475, 7050, and 7010 were among the first alloys developed to satisfy the fracture toughness requirements of new damage tolerance designs.

With current high fuel costs, use of more expensive low density materials such as Al-Li, Metal Matrix Composite (MMC), polymer (epoxy) based composites (PMC), and Fiber Metal Laminate (FML) such as

Glare is predicted [4],[5]. However, introducing these newer materials as substitutes for older aluminum alloys in existing aircraft structures is not usually an option because of the profound implications on structural integrity and airworthiness. In fact even the simple replacement of one aluminum alloy with another must be approached with extreme caution because of unexpected negative consequences.

The focus of this chapter is mainly on aluminum alloys for airframe structures, however engines are also witnessing great innovation, for example with increased use of newer forms of the nickel-based superalloys such as directionally solidified and single crystal blades and vanes [6],[7].

The average age of aircraft in the USAF fleet, which is the largest fleet of aging military aircraft, is estimated to be 26 years and the average age of KC-135 tankers is now 50 years [8]. Civil aircraft operators have chosen to replace their older fleets; however most military aircraft operators choose to extend service life by more frequent inspection and repair. This has led to higher maintenance costs and workload, and reduced availability of aircraft. It should be noted that military aircraft reliability is still based on usage rates, which largely reflect flying hours with less emphasis on absolute chronological age when the time-dependent effects of corrosion would become significant.

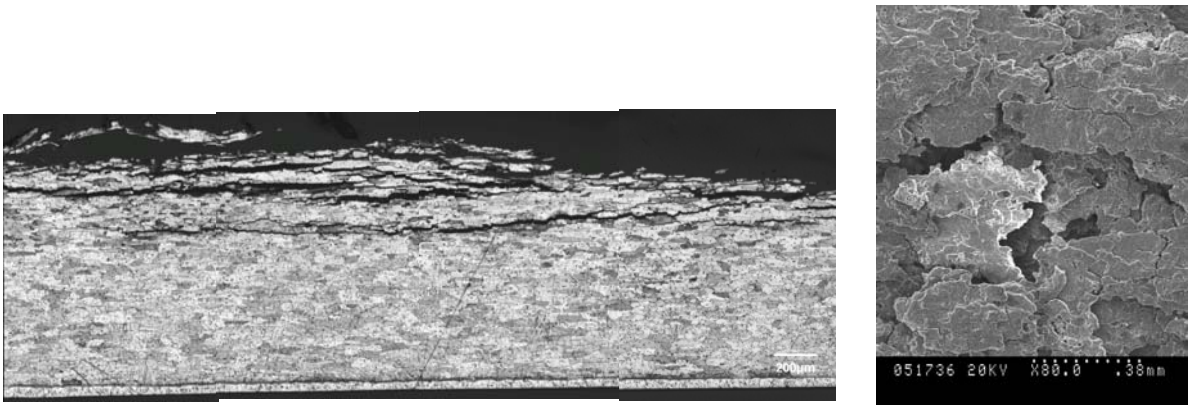
24.2 AGING (LEGACY) ALUMINUM ALLOYS

High strength is the priority requirement for upper wing and fuselage stiffeners, while for lower wing alloys and fuselage skins damage tolerance is key [9],[10]. Most of the older aircraft were manufactured with Alclad 2024-T3 or 7075-T6 aluminum, both of which are precipitation hardenable alloys and hence can be heat treated to achieve high static strength. They are typical of many alloys developed in the late 1930s through to the late 1950s and early 1960s. Dealing with corrosion and fatigue problems of these legacy alloys (2024 and 7075) is the main source of cost in older aircraft. The alloy 2024 has served the aerospace industry since 1935. For the lower wing skin, 2024 was favored because of its higher fracture toughness. Alloy 7075-T651 was introduced in 1944 and has been used for upper wing structures or where high strength is needed in many of the older aircraft. In contrast to 7075-T6, the lower strength 2024-T3 is much more damage tolerant.

There are many parameters considered in the selection of materials for aircraft. However, as aircraft age reliability and maintainability gain considerable importance. There is a high probability of interaction between corrosion and fatigue, and the probability increases as an aircraft ages. In most cases of life extension, the alloys are replaced with the same but unused materials. Parameters influencing the corrosion and fatigue performance of the legacy alloys, such as heat treatment, constituent particles, and surface treatment, are discussed in the following sections.

24.2.1 Heat Treatment

Alloys 2024-T3 and 7075-T6 are both susceptible to exfoliation (Figure 24-1), intergranular corrosion, Stress Corrosion Cracking (SCC), and pitting [11]-[15]. These alloys in general have been the subject of extensive research since their development.



(a) (b)

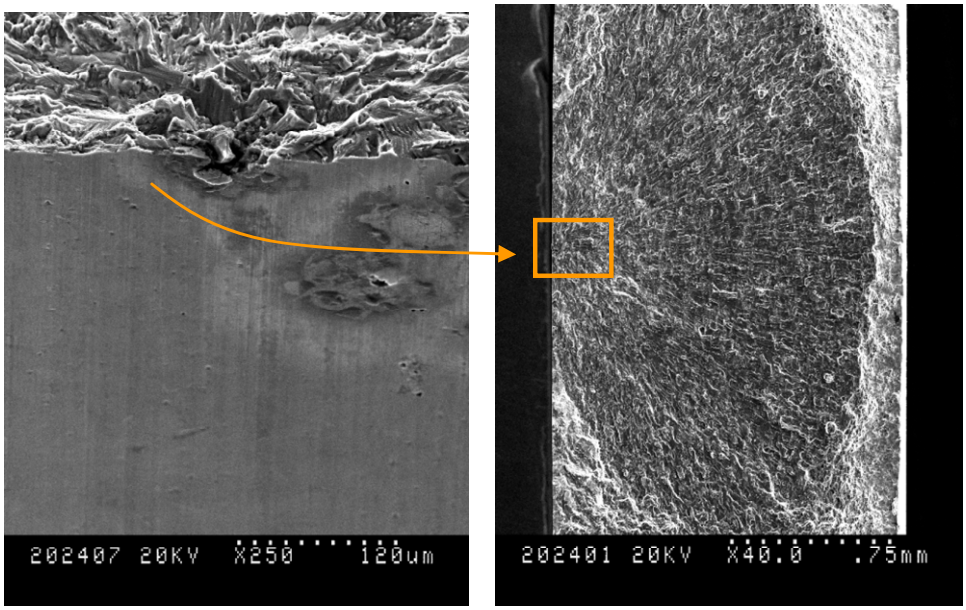
Figure 24-1: The Top Skin of a Severely In-Service Corroded B727 Lap Splice (Faying Surface) Made from One-Side Clad 2024-T3 – (a) Optical micrograph of exfoliation corrosion and a thickness loss of approximately 40%. The sample was taken from (b) SEM micrograph of top view of faying surface [11].

Inadequate corrosion resistance of 7000 series alloys in the T6 temper, particularly in the case of SCC and exfoliation have been the source of many service failures. SCC resistance is extremely important in thick sections. 7075 in the T6 temper and even 2024-T3 for thick products are found to be susceptible to SCC when stressed in the short transverse direction. Unlike general corrosion, the amount of deformation and the degree of observable corrosion accompanying SCC is small and could go undetected using most conventional NDI methods.

SCC in some 7000 series alloys can be overcome by the application of a T7 overaging heat treatment but typically by sacrificing 10 – 20 % strength. The aging treatments such as Retrogression and Re-Ageing (RRA) and T77, however, provide the resistance without considerable sacrifice in strength [16]-[19].

RRA is a multi-stage artificial ageing process and has been demonstrated to improve SCC resistance of 7075-T6 alloys. However, the quench sensitivity of the alloy, apparently due to the chromium-containing grain refinement used, prevents RRA from becoming a common commercial treatment for 7075. By contrast, alloys that are grain refined by zirconium, such as 7050, 7150, and 7055, respond well to the heat treatment which is designated as T77 type. The proprietary T77 temper, developed by Alcoa, is also a multi-step aging treatment that produces a higher strength with matching or better damage tolerance than T76 [8]. Further information on the RRA treatment and variants of it are provided in Chapter 25 [19].

In addition to susceptibility to SCC and exfoliation, the core alloys of 7075-T6 and 2024-T3 are prone to selective corrosion such as pitting along with intergranular corrosion. The fatigue and corrosion failure processes exploit the weakest links within the material, which act as nucleation sites for the fatigue cracks and corrosion (Figure 24-2). For improvement in resistance to localized corrosion, surface treatments such as cladding and anodizing are applied. However, it is found that the benefits gained in terms of corrosion protection by cladding and anodizing could be offset by detrimental effects on fatigue performance [15], [20],[21].



(a) (b)

Figure 24-2: Localized Corrosion (Pitting) Due to Discontinuity at the Surface of an Unclad 1.6 mm 2024-T351 Sheet which Acted as Fatigue Crack Nucleation Site [12]. The fatigue coupon was made from a mildly corroded sheet: (a) Tilted view; and (b) Fracture face with window indicating to the nucleation site.

From the post fracture analysis in these studies, the microstructural features and discontinuities found to be associated with fatigue crack origins in the 7000 and 2000 series materials studied were in order of decreasing severity:

a) Anodizing;

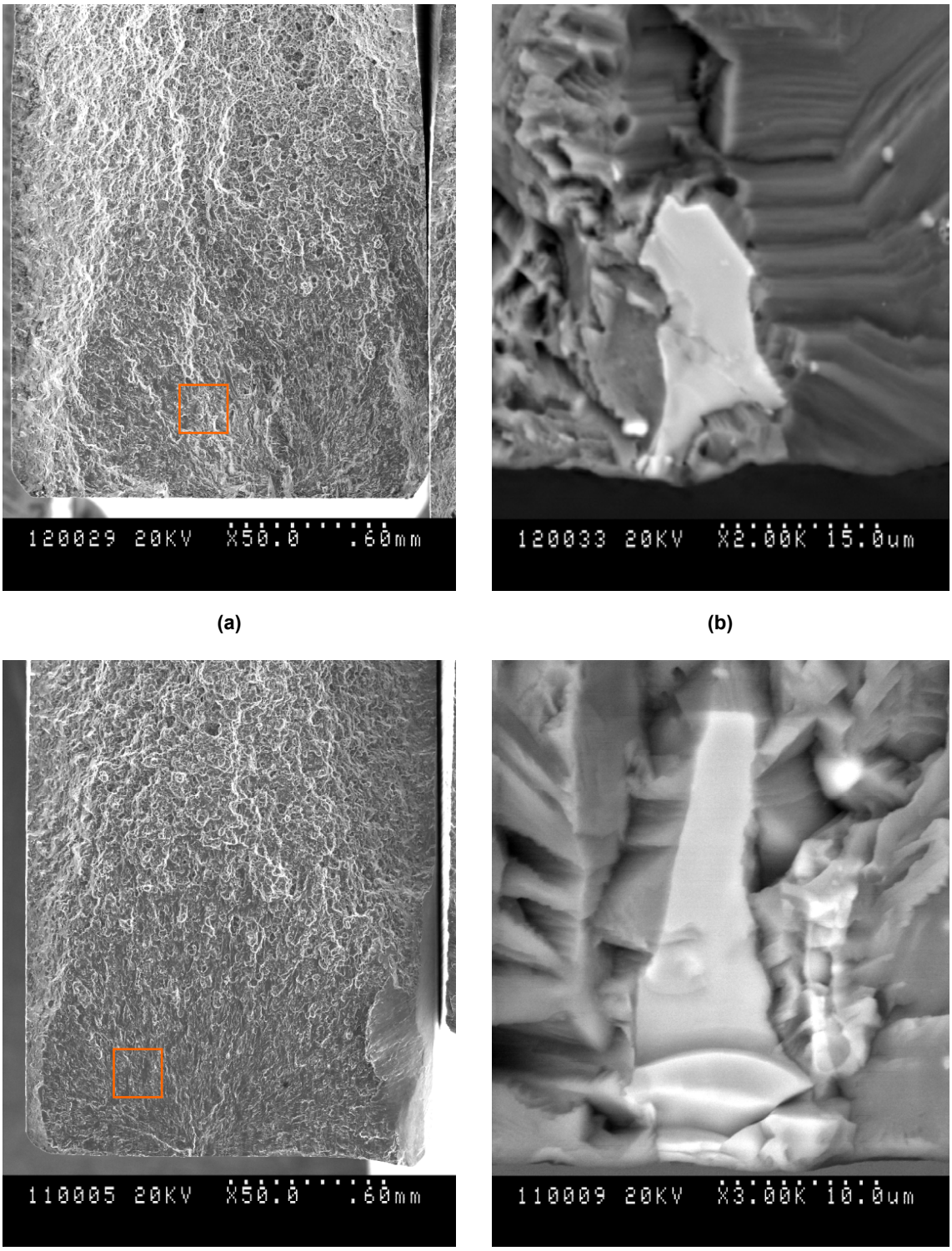
b) Cladding;

c) Constituent particles; and

d) Scratches and machining marks.

24.2.2 Particles

The center of the ingot is the last region to solidify during casting. Porosity and insoluble constituent particles form in this region. Given enough mechanical work in thin gauge sheets, the porosity will generally heal. However, the constituent particles remain and often lie in stringers in the rolling direction of the sheet. Among the major discontinuities that limit corrosion and fatigue performance of the two legacy alloys are constituent particles in the microstructure. Studies have shown that fatigue crack nucleation sites for bare (i.e., no cladding/anodized layer) coupons with acceptable machined surfaces are normally in the vicinity of large constituent particles (Figure 24-3) [15],[22],[23]. The detrimental effects of large constituent particles on the fracture toughness and crack nucleation have also been documented by many other investigators [24]-[29].



(a) (b)

(c) (d)

Figure 24-3: SEM Micrographs of Fracture Surfaces of Fatigue Coupons of 2024-T3 and 7075-T6 Sheets, Indicating Constituent Particles as Crack Origins – (a) Low magnification view of fracture surface for 2024 specimen; (b) High magnification, backscatter view of the (window) nucleation site; (c) Low magnification view of fracture surface for 7075 specimen; and (d) High magnification, backscatter view of the (window) nucleation site [15],[22],[23].

Studies suggest that there are two physically and chemically distinguishable types of constituent particles in these alloys. Larger and more angular particles have considerable amounts of iron, whereas the smaller, spherical particles do not. The chemical composition of the constituent particles from EDX studies taken from a metallographic section was compared with the chemical composition of the particles that were associated with the crack nucleation sites in the failed fatigue coupons. All of the spectra from the fatigue crack nucleating particles were identical to those from analysis of large particles found in metallographic sectioning, as shown in Figure 24-4. It was also evident that the particles that acted as crack origins in fatigue testing were at the high end of the particle size distribution obtained through metallography. Again, large particles only represent a very small fraction of the particle population. According to the ASM Metals handbook [30], the main intermetallic phase for the larger particles associated with crack nucleation is Al_7Cu_2Fe (β-phase).

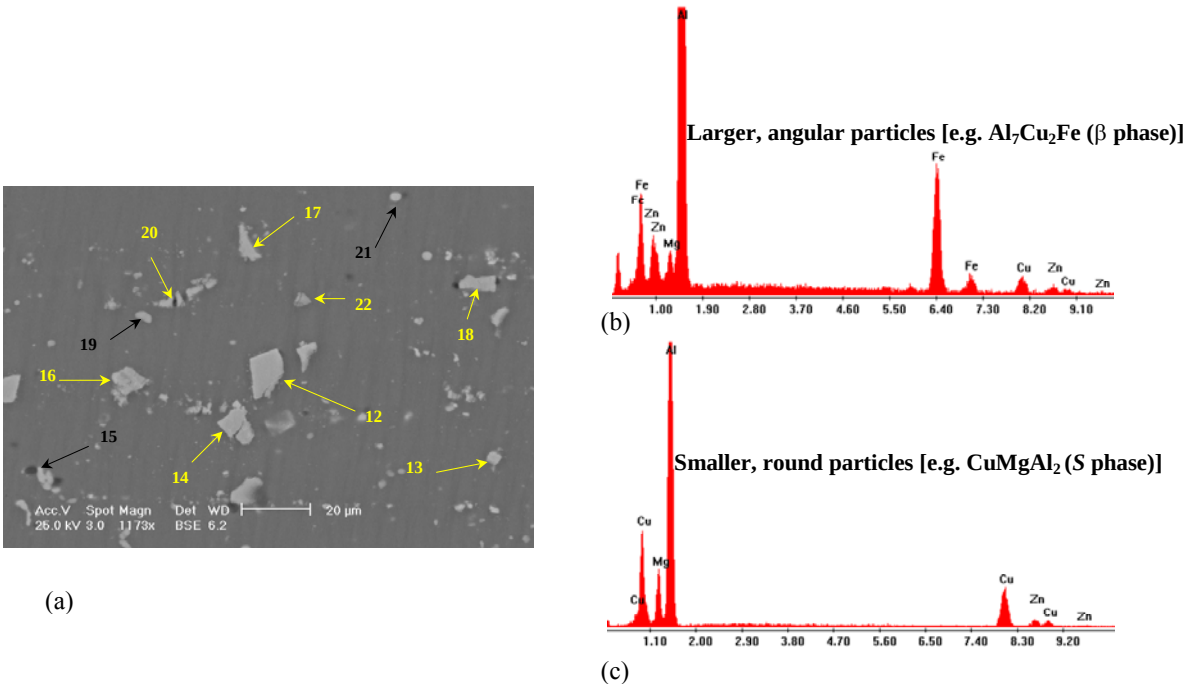
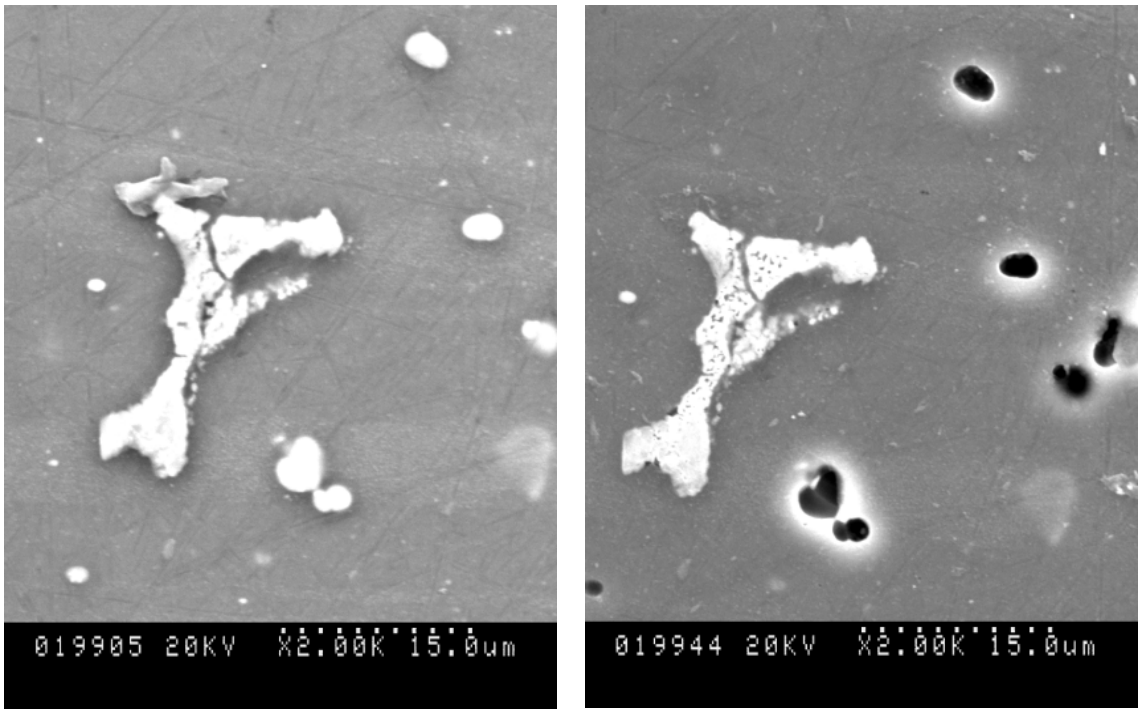


Figure 24-4: (a) SEM Micrograph of Typical Constituent Particles in a 2024-T3 Alloy. EDX results showed that (b) larger and more angular particles have considerable amounts of iron, whereas (c) the smaller, spherical particles do not. The spectra from the fatigue crack nucleating particles were identical to those from analysis of large particles found in metallographic sectioning [22].

Spherical particles seem to be mainly of the $CuMgAl_2$ (S-phase) type. They do not appear to be as harmful as iron bearing β-phase particles to fatigue performance. However, when these alloys are exposed to corrosive solutions, S-phase type particles appeared to be the weak link of the microstructure in terms of initiating pitting corrosion (Figure 24-5).



(a) (b)

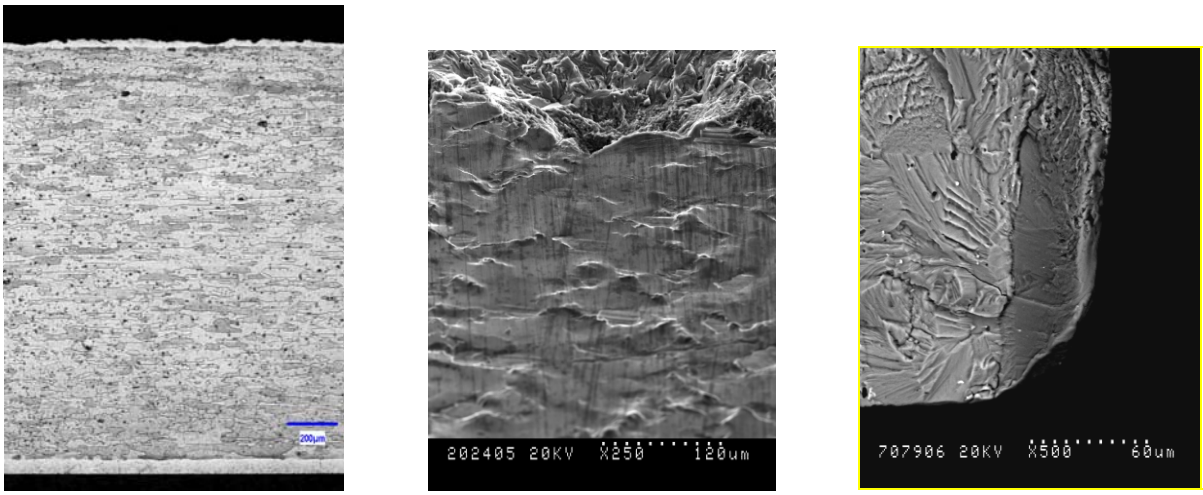
Figure 24-5: Constituent Particles – (a) Prior to corrosion; and (b) After 2 hours in corroding solution. Although, spherical particles did not seem to be harmful to fatigue performance, they appeared to be the weak link of the microstructure in terms of initiating pitting corrosion [22].

The key ingredients of the fatigue nucleating particles in aluminum alloys are impurities such as iron and silicon. Studies strongly suggest that modification of chemical composition and minimizing the volume fraction and size of intermetallic constituent particles can result in improvements in corrosion and fatigue performance. As will be discussed in the following sections, the new derivatives of these alloys have better control of alloy impurities such as Fe and Si, and could be used as replacement alloys.

24.2.3 Cladding/Anodizing

Cladding and anodizing are widely applied surface treatments for the legacy alloys and in general for aging aerospace aluminum alloys to enhance the corrosion performance.

In order to improve corrosion resistance, sheet materials are often clad with more anodic pure aluminum. The role of cladding is to protect the high strength core from localized corrosion attack. The thickness of the cladding layer is generally less than 5% of the overall thickness (~50 μm). The thin clad layer corrodes rather mildly and uniformly to protect the core alloy (Figure 24-6(a)). The yield stress of cladding is very low (10% of core metal); therefore, even under normal operating conditions for core materials, the yield stress of the cladding is likely to be exceeded and induce many cracks (Figure 24-6(b)). These multiple surface cracks in the cladding will assist the earlier nucleation of fatigue cracks and propagation into the core material. They could also raise local mean stress in the core metal because the clad layer carries very little load. It is well known that nucleation and/or early (small) crack growth comprises the major portion (e.g., up to 80%) of the fatigue life [31]-[36]. Therefore, acceleration of the nucleation process would significantly decrease the fatigue life. Studies by Hunter and Edwards [37],[38] showed that on clad specimens, the first crack could be detected as early as 1% of the fatigue life.

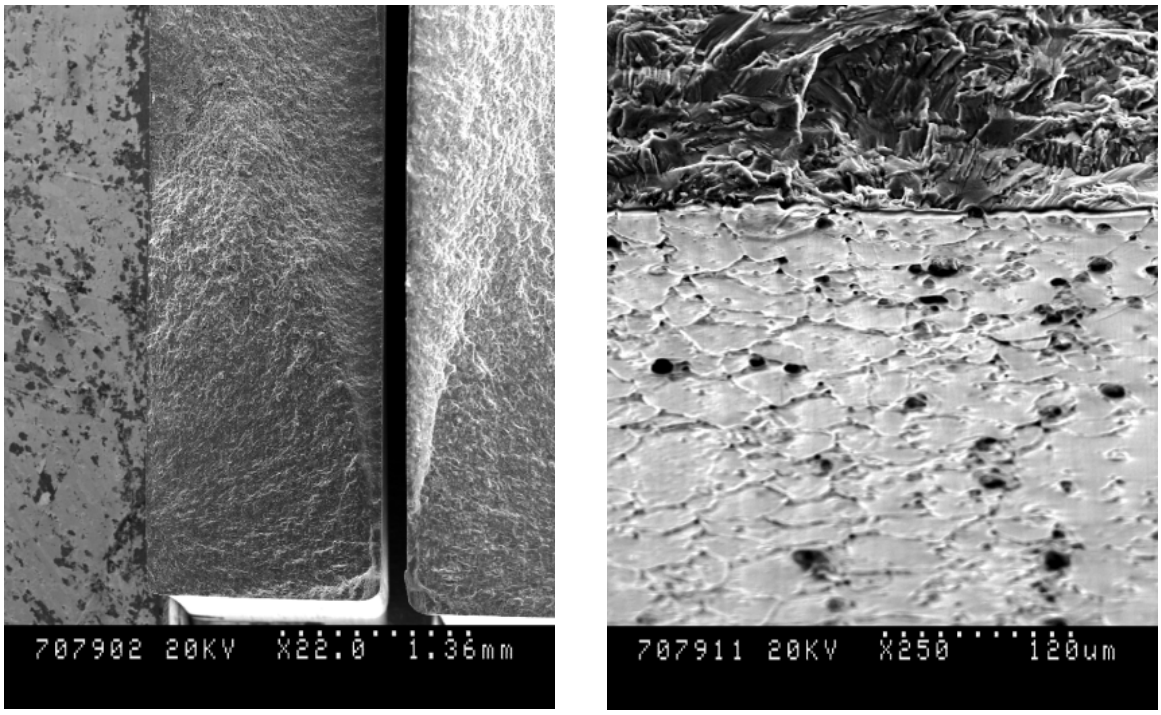


(a) (b) (c)

Figure 24-6: The Thin Clad Layer Corrodes Rather Mildly and Uniformly to Protect the Core Alloy – (a) General corrosion of clad layer at the exterior surface of fuselage skin (top surface) from B727; (b) Tilted image crack nucleation site as indication of severe deformation and cracking at clad layer at the surface of 2024 core alloy which failed in fatigue testing; and (c) Fracture surface showing the clad layer (~ 50 µm) at the right side [15].

Since the clad layer is soft and provides poor adhesion for paint, sometimes an anodic coating is grown on top of the cladding. Anodized coatings are commonly applied to aluminum alloys to provide resistance to corrosion and wear. They are also used as pre-treatments for adhesive bonding and painting [39]. Coatings for corrosion resistance are typically either the thin Type I (1 – 3 µm) or the moderately thick Type II (3 – 25 µm). For wear resistance, thicker hard anodizing (Type III up to 100 µm) is applied [40]. The two main anodizing treatments to achieve corrosion and wear resistance are chromic acid anodizing and sulfuric acid anodizing. The electrolytic process of anodizing produces a controlled columnar growth of amorphous aluminum oxide on the surface of aluminum alloys where the thickness of the oxide film is much greater than those formed naturally.

Anodizing also harms the fatigue life in various ways, with the main effect again being the encouragement of crack nucleation. The anodizing process produces a brittle and hard oxide film with inherent pores, which would readily crack when deformed. The presence of defects in the oxide film facilitates the early nucleation of fatigue cracks (Figure 24-7). The fatigue life of anodized specimens is also affected by the formation of so called “etch pits”. A long etching time (deoxidizing) prior to anodizing could result in pitting, particularly in the vicinity of chemically active regions such as grain boundaries and intermetallic particles at the surface [41],[42].



(a) (b)

Figure 24-7: Fatigue Fracture Surface of Coupons Made of Anodized 1.6 mm Thick 7079-T6 Alloy. The sheet was removed from a retired C-5 fuselage skin – (a) Fracture surface of fatigue coupon with window showing the nucleation site; and (b) Tilted SEM image represents a close up view of nucleation site (the window) indicating a brittle and hard oxide film anodized layer with inherent pores and tiny cracks [13].

24.3 NEW REPLACEMENT MATERIALS

In reaction to the many service failures of the legacy alloys and cost burden on ageing aircraft, there is a continuing demand for better fatigue and corrosion performance. The appeal of aircraft manufacturers to materials scientists has been to manufacture alloys with combinations of good properties such as high strength of 7075-T6, good fracture toughness of 2024-T3, and high corrosion resistance of 7XXX series alloys in the T7 temper. In response to the demand (in particular for thick products), alloy manufacturers have produced new derivatives of 2000 and 7000 series and more recent alloys as shown in Table 24-1. As it was mentioned, the weak links of materials in terms of fatigue and corrosion performance have been constituent particles. Also because of low corrosion resistance of core alloys, they had to be coated (clad/ anodized) at the expense of fatigue performance. Impurity elements, in particular iron and silicon are the damaging ingredients of the fatigue nucleating particles in aluminum alloys, and their reduction is the main modification in chemical composition observed. For instance, modified chemical compositions and reduced volume fraction of intermetallic constituent particles resulted in the development of 2524 alloy and 7475 as derivatives of 2024 and 7075 respectively. As indicated by Table 24-1, these new derivatives have much lower Fe and Si contents (up to 4 to 10 times). Table 24-2 compares and contrasts the mechanical properties of older and newer alloys and materials that might be used as replacements.

Table 24-1: Chemical Composition of Alternative Materials.

Aerospace Al Alloys									
2000 Series	**Cu**	**Zn**	**Mg**	**Mn**	**Fe**	**Si**	**Cr**	**Zr**	**Ti**
2024	4.4	–	1.5	0.6	≤0.5	≤0.5	0.1	–	0.15
2026	3.6 – 4.3	0.1	1.0 – 1.6	0.3 – 0.8	0..07	0.05	–	0.05 – 0.25	0.06
2224	4.1	–	1.5	0.6	≤0.15	≤0.12	–	–	–
2324	3.8 – 4.4	0.25	1.2 – 1.8	0.3 – 0.9	0.12	0.1	0.1	–	0.15
2524	4.0 – 4.5	0.15	1.2 – 1.6	0.45 – 0.7	0.12	0.06	0.05	–	0.1
6000 Series	**Cu**	**Zn**	**Mg**	**Mn**	**Fe**	**Si**	**Cr**	**Zr**	**Ti**
6013	0.6 – 1.1	0.25	0.8 – 1.2	0.2 – 0.8	0.5	0.6 – 1.0	0.1	–	0.1
7000 Series	**Cu**	**Zn**	**Mg**	**Mn**	**Fe**	**Si**	**Cr**	**Zr**	**Ti**
7010	1.5 – 2.0	5.7 – 6.7	2.1 – 2.6	0.1	0.15	0.12	0.05	0.1 – 0.16	0.06
7049	1.2 – 1.9	7.2 – 8.2	2.0 – 2.9	0.2	0.35	0.25	0.1 – 0.22	–	0.1
7050	2.3	6.2	2.25	–	≤ 0.15	≤ 0.12	–	0.1	–
7055	2.0 – 2.6	7.6 – 8.4	1.8 – 2.3	0.05	0.15	0.1	0.04	0.08 – 0.25	0.06
7075	1.2 – 2.0	5.1 – 6.1	2.1 – 2.9	0.3	0.5	0.4	0.18 – 0.28	–	0.2
7079	0.6	4.3	3.2	0.2	≤ 0.4	≤ 0.3	0.15	–	–
7085	1.3 – 2.0	7.0 – 8.0	1.2 – 1.8	≤0.04	≤0.08	≤0.06	≤0.04	0.08 – 0.15	≤0.06
7150	1.9 – 2.5	5.9 – 6.9	2.0 – 2.7	0.1	0.15	0.12	0.04	0.08 – 0.15	0.06
7178	1.6 – 2.4	6.3 – 7.3	2.4 – 3.1	0.3	0.5	0.4	0.18 – 0.28	–	0.2
7249	1.3 – 1.9	7.5 – 8.2	2 – 2.4	0.1	0.12	0.1	0.12 – 0.18	–	0.06
7475	1.2 – 1.9	5.2 – 6.2	1.9 – 2.6	0.06	0.12	0.10	0.18 – 0.25	–	0.06

Al-Li Alloys	**Li**	**Cu**	**Zn**	**Mg**	**Mn**	**Fe**	**Si**	**Cr**	**Zr**	**Ti**	**Other**
2050	0.7 – 1.3	3.2 – 3.9	0.25	0.2 – 0.6	0.2 – 0.5	0.1	0.08	0.05	0.06 – 0.14	0.1	0.2-0.7 Ag
2090	1.9 – 2.6	2.4 – 3..0	0.1	0.25	0.05	0.12	0.10	0.05	0.08 – 0.15	0.15	–
2098	0.8 – 1.3	3.2 – 3.8	0.35	0.25 – 0.8	0.35	0.15	0.12	–	0.04 – 0.18	0.1	0.25-0.6 Ag
2099	1.6 – 2.0	2.4 – 3.0	0.4 – 1.0	0.1 – 0.5	0.1 – 0.5	0.07	0.05	0.1 – 0.5	0.05 – 0.12	0.1	0.0001Be
2199	1.4 – 1.8	2.0 – 2.9	0.2 – 0.9	0.05 – 0.4	0.1 – 0.5	0.07	0.05	–	0.05 – 0.12	0.1	0.0001Be
8090	2.2 – 2.7	1.0 – 1.6	0.25	0.6 – 1.3	0.1	0.30	0.20	0.10	0.04 – 0.16	0.1	–

Table 24-2: Mechanical Properties of Alternative Materials.

Aerospace Al Alloys	UTS (MPa)	Yield Strength (MPa)	Fracture Toughness, K_{IC} ($MPa*m^{1/2}$)	Elongation (%)	Applications
2024-T351	428	324	37	21	Lower wing, skin and stringer, high damage tolerance
2026-T3511	496	365	NA	11	Lower wing, fuselage stringer
2050-T84	540	500	43 (LT)	NA	Thick products, spars, ribs
2090-T83	531	483	43.9	3	Lower wing
2098-T82	503	476	NA	6	Sheet or thin plate
2099-T83	543	520	30 (LT) 27 (TL)	7.6	Floor beams, seat tracks
2199-T8	400	345	42 (LT) 36 (TL)	8	Lower wing skin
2224-T39	476	345	53	10	Lower wing, fuselage stringer
2324-T39	475	370	38.5 – 44.0	8	Lower wing skin
2524-T3	434	306	40 (TL)	24	Fuselage skin
6013-T6	379 359	359	46 (LT)	8	Fuselage skin
7010-T73651	525	455	41 (LT), 33 (TL) 26 (SL)	12	Upper wing skin and stringer, thick products
7049-T73	517	448	33 (LT) 24 (TL)	12	Thick products
7050-T7351	552	490	35 (LT) 31 (TL)	11	Thick products e.g., spars, ribs, landing gear
7055-T7751	614	593	26	7	Upper wing, skin, stringer
7075-T651	572	503	22	6	Upper wing skin and stringer
7079 – T651	540	470	45 (TL)	14	Wing panels, bulkhead
7085-T7651	519	468	29 (LT)	8	Thick products, wing spars
7150-T7751	579	538	24	8	Upper wing, skin, stringer
7178 – T6	590	521	23 (LT)	11	Upper wing skin
7249-T6	592	532	37	11	Extrusion, thick products, wing
7475-T7351	545	476	42 (LT) 37 (TL)	12	Fuselage skin
8090-T851	500	455	33 (LT), 30 (TL) 12.4 (SL)	12	Fuselage skin, stringer, frame
ARALL-1	800 (L) 386 (L+45)	641 (L) 341 (LT)	NA	0.7 (L) 7.1 (LT)	
ARALL-2	717 (L) 317(L+45)	359 (L) 228 (LT)	NA	1.4 (L) 12.0 (LT)	
ARALL-3	828 (L) 373 (L+45)	587 (L) 317 (LT)	NA	1.0 (L) – (LT)	
ARALL-4	731 (L) 338 (L+45)	373 (L) 317 (LT)	NA	1.4 (L) 3.9 (LT)	
Carbon Composite (Typical)	655 (L) 276 (L+45)	–	NA	0.5	
CF/PEEK Composite (unidirectional)	1507 (L) 88 (T)	NA	NA	NA	
GLARE (cross-ply)	717 (L) 716 (T)	305 (L) 283 (T)	NA	4.7	
GLARE (uni-directional)	1282 (L) 352 (T)	545 (L) 333 (T)	NA	4.2 (L) 7.7 (T)	

In the search for improved materials Alcoa developed 7050-T7, as well as 7049, 7249 and 7010 alloys, but among these four alloys the former appears to have the most favourable combination of properties. Alloy 7050 was also developed in response to lower strength of 7075-T73 and for the retrofit of 7079-T6 that showed very low resistance to SCC. In response to demand for higher strength (as high as 7178-T6), the more recent product 7150-T77 was developed, which has higher strength and damage tolerance when compared with 7050-T76 [43]. Another new alloy; 7055-T77 has even higher strength than 7150-T6 alloy. High compression strength, combined with good fracture toughness and good corrosion resistance has made 7055 a good replacement of 7075 for the upper wing skin.

However for lower wing structures where predominantly tensile loading conditions prevail, even the major improvements of the newer 7000 series alloys are not considered adequate and they are not recommended. Where 2024-T3 was the dominant alloy, today alloys 2324 and 2224 are favoured for lower wing skins due to their higher tensile strengths and fracture toughness values and improved fatigue performance. For fuselage applications, 2024 has been replaced by 2524 due to excellent fracture toughness and good tensile strength [44],[45].

Alloy 2524-T3 has approximately 15 – 20 % improvement in fracture toughness and twice the fatigue crack growth resistance when compared with 2024-T3. The improvement helped in the elimination of tear-strap reinforcements in a weight efficient manner on the Boeing 777 [8],[45]-[47].

The 6000 series alloys, and in particular 6013-T6, have been considered to replace 2024 on a number of US Navy programs. They are weldable and less expensive, and do not need cladding. Nevertheless, they are still susceptible to intergranular corrosion similar to 2024-T3 [48],[49].

Under pressure from competing polymer-based composite for structural applications, Al-Li has been a new thrust for the aluminum industry. The aerospace industry saw the benefits of a high strength metallic alloy since it allowed use of the same tooling and assembly techniques as the more conventional Al alloys. It also involved lower risk, requiring no new repair and maintenance methodologies and avoided the recycling issues of composites. Both Li and Be are exceptions among other elements in that despite being lighter than Al, they increase the stiffness of the aluminum. Al-Li alloys are lighter in weight and higher in stiffness compared to conventional aluminum alloys. Al-Li began with high promise, and since high stiffness is one of the major design factors for airframes, there were good opportunities for Al-Li. The second generations of these alloys with 2 – 3% lithium, such as 2090 and 8090 have been used in the MIG 29 and Cormorant (EHI) Helicopter. However, these early versions of Al-Li in particular, did not live up to their initial promise and until now have seen only limited use in airframes. Their major shortcomings were delamination and lack of ductility. The third generation alloys with much lower lithium content (2098, 2099 extrusion and 2199 sheet) are claimed to eliminate the problems with high planar anisotropy, poor ST properties, and low fracture toughness [50]. It is believed that the new generation of Al-Li alloys will find widespread usage in future commercial aircraft. The other new alloy, although with much higher cost, is Al-Mg-Sc which has excellent corrosion resistance and can be used as skin requiring minimum maintenance [60].

Titanium alloys also can be used where there is a need for much better resistance to corrosion (almost immune to exfoliation) and where there is a need for physically smaller components, for example landing gear components of the B777. They are even good replacements for high strength steel due to elimination of the risk of hydrogen embrittlement and need no protective coating. Ti alloys also exhibit good galvanic compatibility and nowadays are extensively used for attaching aluminum to carbon fiber composites for repair purposes. In construction of new hybrid structures, the use of Ti fittings is generally recommended.

24.4 LESSONS LEARNED

It is often best to review past examples of important developments and misjudgments to provide guidance for the future. The objectives for introducing new materials are to improve performance, reduce the cost

(both the purchase cost and the maintenance cost), extend service life, and reduce environmental impact. There is always interaction among these factors that have to be balanced to reach an overall improved performance.

For example if stiffness were the main limiting factor for a component, honeycomb structure would be ideal. However, not all of the materials can be fabricated this way and also there is a tendency for corrosion to occur in this type of construction. Metal Matrix Composites (MMC), either aluminum based or titanium based, with SiC (or Al_2O_3) particles also provide high stiffness, but low ductility in the current product forms has limited their application.

Another example is the development of the very highly alloyed 7178-T6 in 1951 as a replacement for 7075-T6. The increased demand in the aircraft industry for higher strength–to-weight ratio material led to a record peak in strength from this aluminum alloy. It was used for the upper wing skins of aircraft in both extruded and rolled forms and was used on Boeing 707 aircraft and lower wing skin of KC-135 [8],[51]. However, due to the lack of damage tolerance and the need for high fracture toughness and high mechanical reliability, this alloy was gradually withdrawn from use. High strength 7055 has been a good replacement for 7178, with much improved fracture toughness [43].

It is also important that new materials achieve maturity before being used in aircraft. Experience with alloys in service, perhaps in aircraft secondary structures or non-aeronautical applications or simulated service behavior concerning corrosion, inspection, long term performance, etc. should be known prior to use in aircraft primary structure. A good lesson from the past is the launch of the high strength alloy 7079 in T6 temper for thick products. The alloy was introduced as a replacement for 7075-T6 to improve SCC performance in the short transverse direction. Laboratory tests in 3.5% NaCl solution by alternate immersion showed superior performance to the alloys in use at the time. Despite the good resistance predicted by the accelerated testing, service failures of alloy 7079-T6 showed it to be by far the most SCC susceptible alloy and temper among the commonly used high strength aluminum alloys available at that time. Although it was resistant to nucleation of SCC cracks, the rate of growth of SCC was orders of magnitude faster than that of the other alloys. The pre-cracked SCC test was not a standard test at the time in early 1950s. Figure 24-8 shows the nature of the crack paths for EAC in aluminum alloys which are almost exclusively intergranular [14]. Widespread service failures resulted in recommendations that 7079-T6 be replaced with alternative materials such as 7475-T7 [10].

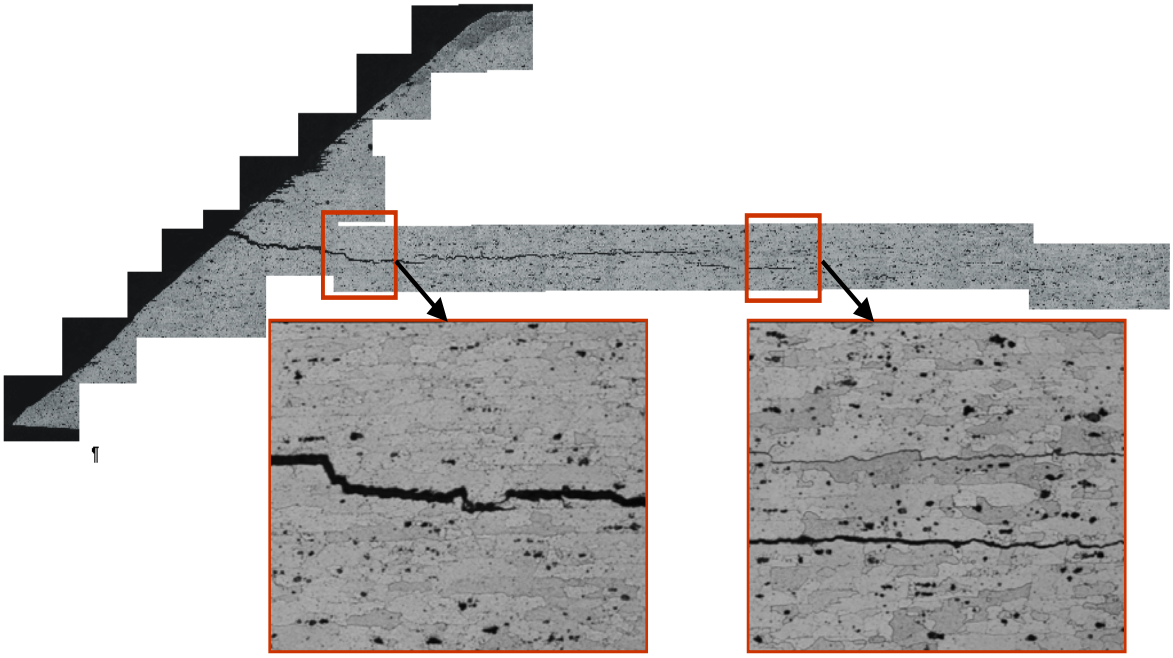


Figure 24-8: SCC Failures During Service at Mid Thickness of a Sheet Made of Alloy 7079-T6. Section of rivet hole, displaying a 4 mm (0.157") long crack. Crack at fastener hole on a fuselage panel near the troop door of C141 Starlifter [14].

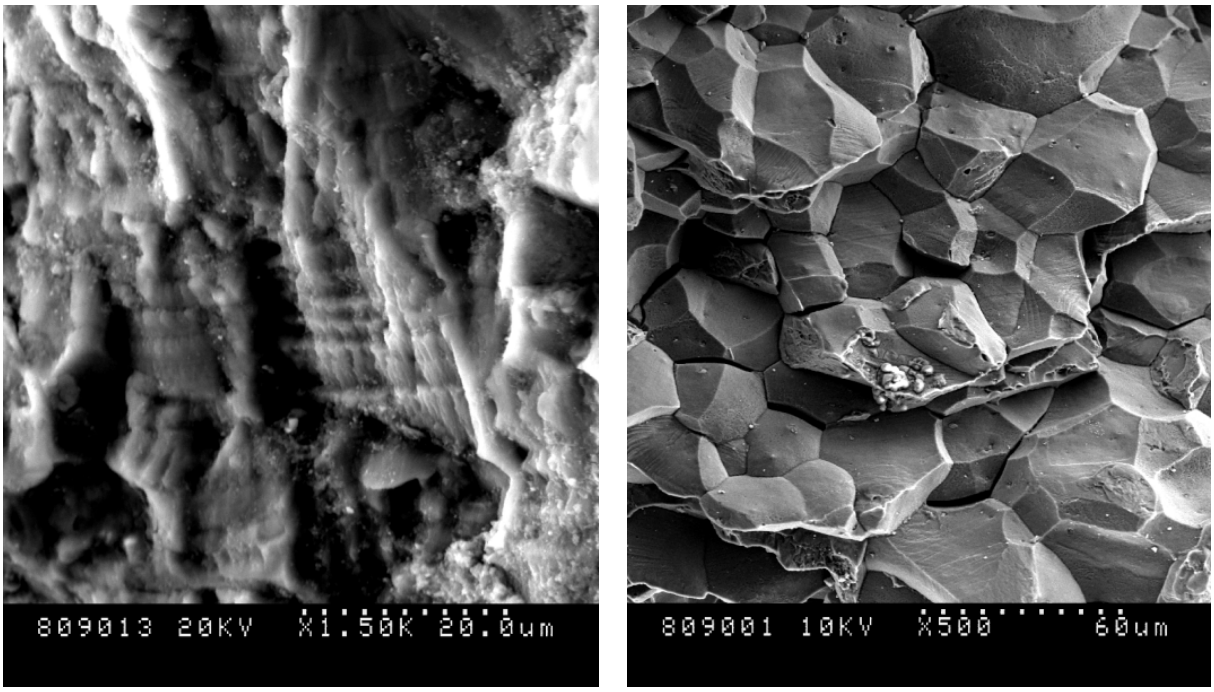
Introducing new replacement materials should not be done in a radical way. New materials should be derivative alloys that have been developed by gradual changes in composition or temper. Brand new materials will face qualification and certification issues, high substitution risk and higher manufacturing costs. For instance, although polymer matrix composites are used in Airbus and Boeing (777 & 787) aircraft, they are not generally recommended as replacements for conventional aluminum airframe materials. They could alter the load distributions in the airframe, center of gravity, and affect vibration signatures of the structures.

Other examples of hasty introduction of materials into service are Metal Matrix Composites (MMC) in the form of discontinuous or continuous reinforcement, along with aluminum lithium alloys. The first few versions of these products had very limited success when incorporated into aircraft due to lack of ductility. The next generations of these materials have had fewer problems; however, the earlier bad experiences discouraged their widespread use and they have never achieved their full potential as structural alloys. Long term performance, substitution risk, prior in-service experience, results of full scale testing and life cycle costs of the new replacement material have to be considered before any attempt can be made to insert them into service.

The low density and good mechanical properties of Al-Li alloys make them attractive for many structural applications. Known applications of Al-Li alloys in military and civilian aviation are: EH101/CH149 structure; F-16 bulkheads and fuselage structure; hydrogen tank of NASA's space shuttle; and fuselage skins of Russian BE-103 amphibious aircraft and Tupolev business class aircraft [52]-[55].

In the case of the CH149 Cormorant Search and Rescue Helicopter, 8090 Aluminium-Lithium (Al-Li) alloys in different product forms and tempers have been used to replace most of the conventional aircraft alloys such as 7075-T6 and 2024-T3 [56]. This is because of their low density and high elastic modulus. Although the Cormorant is in the early stages of its life cycle, signs of premature material failure are raising concerns about long-term durability. The fracture surfaces of a number of in-service failed Al-Li parts indicate that brittle intergranular fracture is the most common mode of failure (Figure 24-9).

The study also points out the possibility of embrittlement of Al-Li over time when exposed to temperatures between 30°C and 160°C which is within the operational envelope. Table 24-3 outlines where the Al-Li alloys are used in aircraft and the conventional alloys they replaced [57].



(a) (b)

Figure 24-9: Typical Fracture Feature Found During Maintenance Inspection of the CH149 Cormorant at the Secondary Structures (Under-Floor Z-Stiffeners) After Only a Few Years of Service. The most common failure mode observed was (a) small area of fatigue followed by (b) major part of fracture as brittle intergranular failure. The part is made of 8090-T8 aluminum lithium [56].

Table 24-3: Al-Li Alloys Used in the CH149 Cormorant [52].

Product Form	Temper	Substitute For	Applications
Sheet	8090-T3 (as-received)	–	Floor installations, brackets, stiffeners, frames, spars, stringers, longerons, ribs, bulkheads, tail cone skin
	8090C-T8 (medium-strength)	2014-T6	Flying control system and avionics bay structures, nose cap, cabin roof frames
	8090C-T81 (damage-tolerant)	2024-T3, 2024-T42	Flying control system structure, skin panels (in lower fuselage), cabin roof frames, flat roof panels
	8090-T84 (medium-strength)	–	Z-stiffeners
	8090C-T621 (damage-tolerant)	2024-T42	Sponsons, repairs
Forging	Cold compressed 8090-T852 (medium-strength)	7010-T7451	Cabin roof and side frames (frames, stringers, joints, intercostals)
	Non-cold compressed 5091-H112 (medium/high-strength)	7075-T73, 7010-T7451/T74	Landing gears
Extrusion	8090-T8511 (medium-strength)	7075-T7351/ T73510/T37511	Frames, brackets, stringers, bulkheads, door rails, seat tracks

The 8090 alloy may have only been evaluated using small-scale coupons, since this author has found no evidence in the literature of component or full-scale tests of these alloys. The manufacturers of Cormorant conducted the large-scale tests and prototype flight trials using the original materials (2XXX and 7XXX series alloys).

As a result of their high stiffness, Al-Li components can alter load paths and distributions within the aircraft's structure, affecting the inherent vibration signature and creating several new, unexpected fatigue-susceptible areas (e.g., in the nose under the pilot seat structure). The more recent (third generation) alloys with much lower lithium content (2098, 2099 extrusion, 2199 sheet) are claimed to be more isotropic, have better ST properties, and improved fracture toughness.

In addition, replacing the old materials with new ones could affect center of gravity for the vehicle, change vibration signature, and increase the probability of galvanic corrosion due to incompatibility with adjacent materials.

Airbus has considered a more evolutionary approach, which is preferred since past experience has shown that every technology has some initial technical problems. Application of any new material in primary structure such as carbon fiber reinforced plastics, fiber metal laminates (Glare and ARALL) and glass thermoplastics requires the establishment of a good materials and design database.

24.5 COMPOSITE MATERIALS

Material and assembly costs (first costs), maintenance costs, and performance are three main drivers for material selection. For instance, polymer based composites and hybrid materials such as Glare have high first cost but are excellent in damage tolerance and corrosion resistance which translates to low maintenance and high performance. For instance the B787 with 50% composite is promising twice as long operation time

between scheduled maintenance intervals of the B767 it replaces [4]. Polymer matrix composites use glass, carbon, aramid, or boron fibers as the reinforcement, with the matrix being either thermoplastic or thermosetting. They outperform aluminum alloys in specific strength, modulus and fatigue; however initial cost of the material can be as much as 10 to 20 times higher than that of aluminum alloys. In general, advanced or new materials are offered at higher costs compared to the existing materials.

The most common matrix resins are thermosetting epoxy resins, which can be used to temperatures as high as 175°C and are compatible with all common reinforcements. These also possess fatigue strengths significantly superior to aluminum alloys. Bismaleimides and other thermosetting polyimides offer increasing temperature capability from 250 – 315 °C. Thermoplastics such as PEEK (polyether ether ketone) are processed beyond their melting points and are tougher than the thermosets, but soften at higher temperatures because of the lack of cross-linking. Many are also less resistant to environmental effects. The cost of processing polymer matrix composites is significantly higher than equivalent metal structures. Lower-cost processes such as resin transfer molding have been improved to allow a high volume fraction of fiber than in previous generations of liquid molding processes. The embedding of smart sensors and actuators adds an additional dimension to the use of composite materials in terms of health monitoring of structures made of such materials.

Laminates of aluminum and polymer composites provide exceptional fatigue-crack-growth resistance and damage tolerance at high specific strength. Although earlier predictions on the increase in use of Al-Li alloys, intermetallics, and ceramics have often been overly optimistic, hybrid laminates of titanium alloys, aluminum alloys, and reinforced polymers are considered to provide combinations of properties beyond the capabilities of the current materials.

24.6 PROCESSING TECHNOLOGIES

One of the ways for the aluminum industry to compete against the composite challenge is to integrate design concepts and advanced manufacturing technologies. Casting and new robust joining techniques for similar and dissimilar materials will enhance such an integration process by eliminating the need for mechanical fastening of separately manufactured parts.

Although cost reduction is a primary reason for use of castings for aircraft structures, by reducing the number of joints, benefits such as improved corrosion resistance can also be realized. However, the poor reproducibility and inconsistency in mechanical properties of conventional castings has introduced the concept of the casting factor as a safety measure. However, by improvements in processing, use of aluminum castings is being increased even in primary structures, e.g., Airbus cargo and passenger doors [58].

Almost all engineered products are made from a number of components. Choosing the best way to joint them together is essential. The combination of new design, advanced manufacturing processes such as Friction Stir Welding or laser welding, and new materials (extruded Al-Li) is capable of producing integrally stiffened panels that offer significant cost and weight savings. One of the shortcomings associated with the use of Al alloys relates to the problems encountered in their joining. Riveting adds unnecessary weight, and fusion welding processes can introduce solidification defects such as porosity and solidification cracking. Friction Stir Welding (FSW) is one of the most promising processes to replace riveting [59]. The process can be used to join aluminum alloys that have traditionally been considered non-weldable. It can also be used to join dissimilar metals.

24.7 CONCLUSIONS

Aging aircraft are increasingly experiencing fatigue and corrosion related cracking problems that pose significant challenges in terms of keeping air operations safe, reliable and economic. The aging materials

and structures have to be repaired or replaced. Since the early fleets entered service, significant progress has occurred in alloy development and manufacturing processes. Combination of the new materials and the new assembly processes could reduce the maintenance burden and sustain vehicle airworthiness.

Tighter control on composition, fabrication processes and heat treatment has enabled alloy manufacturers to achieve superior microstructures which lead to optimum tailored properties. Alloys are being developed that have inherent corrosion resistance and which are less critically dependent on supplementary corrosion protection such as via cladding and anodizing. One example is the weldable and corrosion resistant aluminum-magnesium-scandium alloy [60].

Solid state friction stir joining with its low heat input allows for a higher portion of base metal strength to be retained. Friction stir and laser beam welding can be used as repair processes or as alternatives to riveting process.

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