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Materials Science and Engineering Fundamentals

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Materials Failure: Wings of an Airplane made of Aluminum Alloy

A case study submitted in partial fulfillment of the requirements in the course

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Definition of the Problem

Aluminum, the second most abundant metallic element on the planet, has become an economically competitive engineering material. The emergence of industrial advancements, by creating a demand on material characteristics with the unique properties of aluminum, paved the way to the use of alloying metals. Aluminum alloys are a mixture of aluminum and other elements such as magnesium or silicon. As opposed to pure metals, alloys enhance material characteristics which is subsequent to expanding its wide range of applications.

In the aerospace industry, high-strength aluminum alloys have been the primary material choice of aircraft components, specifically the wings of an airplane, since the 19th century. Other properties that were taken into consideration were its low structural weight, safety, higher fracture toughness, and high corrosion resistance (Staley, 1996). However, when subjected to different environmental conditions, deterioration of the mechanical properties could possibly occur. Airplanes fly at very high altitudes around 38,000 to 40,000 feet above the ground. Pressure and temperature varies dependently on the altitude. At lower heights, aircrafts experience higher pressure and temperature. Contrarily, at higher altitudes, the pressure and temperature is lower. As airplanes move up, they are exposed to varying conditions. These recurrent changes could provide a risk of material failure. For instance, corrosion generally happens resulting from atmospheric oxidation of the surface. Moreover, repeated exposures from straight-and-level flight, turning, accelerating, decelerating and other maneuvers causes changes in the loading of the aircraft wings. As a result, the component would likely fail by fatigue (Dwivedi, 2021).

This case study aims to have an in-depth investigation of the aluminum alloys in the wings of an airplane that are susceptible to material failure by identifying the composition of the material, the service conditions of the material, the mechanical properties and their corresponding tests for the mechanical properties, and mechanisms by which the material will likely fail.

Composition of Material

Aluminum alloys are divided into two categories: cast and wrought conditions. Historically, wrought products are used for primary aircraft structures, while casts are employed in secondary structures. A wing of an airplane is considered as a primary structure. It is a beam that transmits the entire applied air load to the fuselage's center attachment. The composition of the material in the wings varies depending on the type of aircraft. Moreover, only a limited number of alloying elements have important additions to the aluminum alloy. A system has been created that classifies the alloys according to the principal alloying additions that are contained in the alloy. Shown in tables 1 and 2 are the aluminum alloy designations either in four- or three-digit series and their corresponding main alloying elements.

Table 1. Aluminum alloy designations with four-digit series

Four-digit series	Al content or main alloying elements
1XXX	99.0% minimum
2XXX	Copper
3XXX	Manganese
4XXX	Silicon
5XXX	Magnesium
6XXX	Magnesium and Silicon
7XXX	Zinc (most also contain Mg)
8XXX	Others e.g. Lithium
9XXX	Unused

**Bhat, B. N. (2018). Aerospace materials characteristics. Aerospace Materials and Applications, 11–208.*

Aluminum alloys that are identified by a four-digit numbering system have its first digit representing the major alloy group. Other numbers represent other alloys that are present in it. Specifically, the second digit is an indication of the alteration of the original alloy, which we refer to as impurity limits while the remaining digits identify the specific aluminum alloy. For example, as presented in Table 1, the 3XXX series is reserved for alloys which contain manganese; the 7XXX series is composed of mostly Zinc and/or small additions of Magnesium, and the 9XXX series is unused or meaning to say has not been used in naming a series.

Table 2. Aluminum alloy designations with three-digit series

Three-digit series	Al content or main alloying elements
1XX.0	99.0% minimum
2XX.0	Copper
3XX.0	Silicon, with added Cu and/or Mg
4XX.0	Silicon
5XX.0	Magnesium
6XX.0	Unused
7XX.0	Zinc
8XX.0	Tin
9XX.0	Others

**Bhat, B. N. (2018). Aerospace materials characteristics. Aerospace Materials and Applications, 11–208.*

The three-digit numbering system, on the other hand, is somewhat different from the four-digit series system. The first digit in the series refers to the principal alloying element, and the last two digits identify a particular composition. As an example, the 3XX.X series is composed of mostly Silicon with small traces of copper and/or magnesium, the 2XX.X series is used for alloys containing copper as its major alloying composition, and the 6XX.X series is unused (Bhat, 2018).

Table 3. Chemical composition of some 2XXX, 7XXX, and 8XXX Aluminum Aircraft Alloy series

Alloy	Li	Cu	Mg	Mn	Zn	Fe
2024	-	4.4 wt.%	1.5 wt.%	0.6 wt.%	-	< 0.5 wt.%
7050	-	2.3 wt.%	2.25 wt.%	-	6.2 wt.%	< 0.15 wt.%
8090	2.4 wt.%	1.3 wt.%	0.9 wt.%	-	-	0.30 wt.%

**Selvan, P., Pughalendi, P., & Raj, P. (2021). A Review of Aluminum Alloys in Aircraft. Journal of Huazhong University of Science and Technology.*

Shown in table 3 are the chemical compositions of common aluminum aircraft wings alloy series. It can be observed that 2024 alloy, based on the four-digit numbering system, is alloyed with copper as its main alloy group. In this case, it is composed mainly of 93 wt.% Aluminum that is alloyed with 4.4 wt.% copper. It is also important to note other components such as magnesium, manganese, and iron. Most 2XXX series enhance the strength of the material; hence are suitable for places where damage tolerances and high resistance to fatigue crack growth, such as wings, are required (Selvan et al., 2021).

The 7XXX series has their main components alloys zinc. The 7075 alloy is the most common of the 7000 series. The addition of zinc coupled with other alloying metals such as copper or magnesium adds to the stiffness, toughness, and shear strength abilities of the material (Zhou, 2021). However, the drawback of this alloy is it has low resistance to corrosion.

The Lithium-aluminum alloys such as in 8XXX series, which are alloyed with the lightest metal, lithium, are newer materials for airplane wings. The inclusion of lithium improves the specific strength and stiffness of the material. It also provides a very low density which is very appropriate for the upper and lower wing parts (Wanhill & Bray, 2014). Aside from it, Al-Li alloys have low operating and repairing costs (Selvan et al., 2021).

Table 4. Material composition of the wings in commercial aircraft.

Aircraft	**Aluminum**	**Steel**	**Titanium**	**PMC's**	**Other**
Boeing 747	81 wt.%	13 wt.%	4 wt.%	1 wt.%	1 wt.%
Boeing 757	78 wt.%	12 wt.%	6 wt.%	3 wt.%	1 wt.%
Boeing 767	80 wt.%	14 wt.%	2 wt.%	3 wt.%	1 wt.%
Boeing 777	70 wt.%	11 wt.%	7 wt.%	11 wt.%	1 wt.%
DC-10	78 wt.%	14 wt.%	5 wt.%	1 wt.%	2 wt.%
MD-11	76 wt.%	9 wt.%	5 wt.%	8 wt.%	2 wt.%
MD-12	70 wt.%	8 wt.%	4 wt.%	16 wt.%	2 wt.%

**Starke, E., & Staley, J. (1996). Application of modern aluminum alloys to aircraft. Progress in Aerospace Sciences, 32(2–3), 131–172.*

The table above are some lists of common commercial aircrafts and their corresponding material composition. Steel, another alloy, which is a mixture of iron, manganese, silicon, copper, and other alloying elements, is used as the primary alloying material in the aircrafts. Titanium and some polymer matrix composites are also alloyed.

Service conditions of the Material

A material's fracture behavior is influenced by its service conditions, in addition to its inherent mechanical properties. In an aerospace industry, an airplane's wings generate the majority of its lift. Wing structures are responsible for carrying some of the aircraft's heaviest loads and many elements influence the wing's design, including the aircraft's size, weight, speed, rate of climb, and the intended usage. Under the intense strains of combat maneuvers or wing loading, the wing must be built to maintain its aerodynamic form (Harvell & Longmuir, 1990).

The external environments of the aircraft include taxiing, takeoff, cruise, and descent; outside temperature from below −55°C (−65°F) to over 50°C (122°F); ambient pressure from about 10.1 kPa (1.5 psi) to 101 kPa (15 psi); and water content from virtually dry to greater than saturation. Temperature and exposure to gas, liquid or solid media may adversely affect the damage tolerant capability of the material hence aluminum alloy should be used at temperatures above their ductile to brittle transition temperature since it loses its strength at high temperature. Although there is no direct analytical relationship between fracture toughness and ductile to brittle transition test data, ductile to brittle transition data can be a good starting point for qualitative evaluation of material fracture behavior as a function of temperature, particularly for high strength steels (McGill, 2018). The effects of cumulative exposure at service temperatures should also be considered for material that experiences cyclic use at or near the aging or precipitation heat treat temperatures of the material. Repeated exposure at these temperatures can lead to changes in material toughness, ductility and crack growth rates.

Aluminum alloys can be particularly susceptible since their aging temperature is relatively low. Aluminum alloy should also withstand other service environments that may degrade material performance, such as, hydrogen rich environments, low pH environments, chlorine rich environments, and liquid metal or solid metal embrittling environments.

Specific Mechanical Properties of Material

The mechanical properties of a material, which in this case is an aluminum alloy used in an airplane's wings, must be compatible with the service conditions as these likewise are considered when selecting a material for a certain application and purpose. The mechanical properties that aluminum alloy must possess in order to meet the aforementioned service conditions above include stiffness, strength, fracture toughness, fatigue resistance, and corrosion resistance.

Most modern airplanes have comparable wing structures. The wing is essentially a structure made up of spars and ribs that is covered with metal. The wing's major structural parts are the spars which stretch from the fuselage to the wingtip. The spars take up the entire weight carried by the wing which are meant to be extremely flexible (Harvell & Longmuir, 1990) hence the stiffness is determined by finding Young's modulus. A material's Young's modulus is a fundamental attribute that cannot be modified while it is inside its elastic limit. It describes how readily a material may bend or stretch in response to changes in temperature and pressure. A material begins to distort when it reaches a specific stress point. Since every material reacts to stress differently, the Young's modulus is a key constant for engineers across all fields.

Commercially pure aluminum has a tensile strength of roughly 13,000 psi, despite its lightweight weight. The metal's strength is roughly doubled when it is cold worked. To increase strength, aluminum is commonly alloyed with elements like manganese, silicon, copper, magnesium, or zinc. Cold working can strengthen the alloys, while heat treatments can further strengthen and harden certain metals. Aluminum has its own anti-corrosion mechanism in addition to a high strength-to-weight ratio and superior formability. When aluminum is exposed to air, it creates a strong, tiny oxide covering that protects the metal from the elements. Aluminum is not present in nature; it only exists as a compound due to the strong chemical oxide link.

Corresponding Tests for the Identified Mechanical Properties

The aerospace engineer must understand the mechanical and durability properties of materials to ensure they function over the design life of the aircraft component without the need for excessive maintenance and repair. Unfortunately, many of the mechanical and durability properties of materials cannot be calculated using mathematical models and therefore must be measured. With this, they must be measured under standardized and controlled test conditions.

Tension test

One of the most common and important procedures for determining the mechanical properties of materials is the tension test. The tension test is popular because it can assess a significant number of properties in a single test: elastic modulus, strength, ductility, and other properties. Moreover, this test is very simple, quick and inexpensive.

The tension test measures the resistance of a material to a slowly applied pulling force. Figure 1 shows the design and equipment for the test. A coupon specimen made of the test material is held at the two ends by the grips of the tensile machine. A tension (pulling) force is applied to the specimen by holding one end firm and forcing the other end away. A strain gauge or extensometer is attached to the specimen to measure the material extension under increasing force. The reaction of the material to the pulling force until it breaks is recorded and analyzed. This data is used to quantify how the material responds to tensile forces applied in practical situations such as airframes and engines (Ramamurty, 2001).

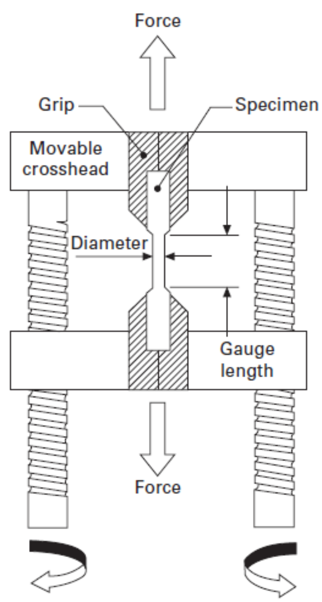

Figure 1. Tensile test setup

Compression test

Mechanical properties of materials under crushing loads are determined by a compression test. Like many other aircraft structures, the upper wing surface of an airplane carries compression loads during flight hence the mechanical behavior of the material must be determined through compression testing (Mouritz, 2012).

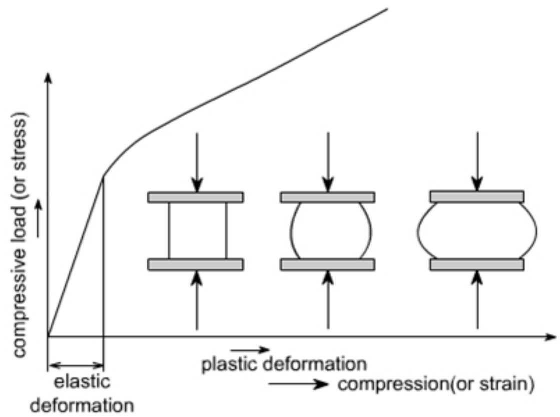

Figure 2. Compression test diagram

The compression test involves squashing a small material specimen under increasing load until the point of mechanical instability as shown in figure 2. Compression specimens are usually short, stubby rods with a short length L to wide diameter D ratio (usually $L/D < 2$) to prevent buckling and shearing modes of deformation. During the test, the reaction of the specimen to an increasing compression force is monitored, and the compression stress–strain curve is generated. Since the elastic modulus is the same, the compression curve is essentially the opposite of the tension curve at small strains within the elastic regime. The discrepancy between the compression and tension curves often becomes large as the strain increases. The specimen becomes shorter and wider as it is crushed, and the load required to keep it deforming increases. Since the specimen in this case does not neck, the stress increases until cracking occurs. The main mechanical properties which are determined from the compression test are the compression modulus and compressive yield strength (Ramamurty, 2001).

Hardness test

Hardness is a material's resistance to permanent indentation. It is not a precisely defined engineering characteristic compared to elastic modulus or yield strength, however, it provides fair information on a material's resistance to plastic deformation. The hardness of ductile materials is related to their yield strength, and the hardness test is frequently used to measure strength (Chawla & Meyers, 2003).

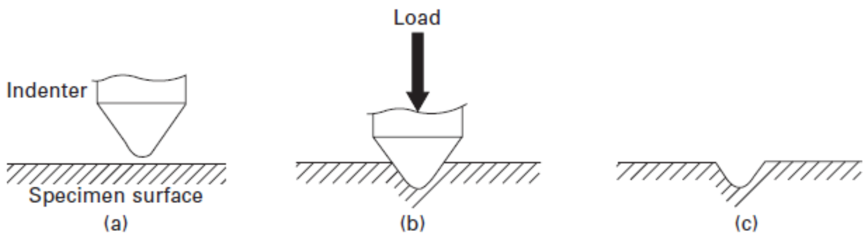

Figure 3. Hardness test diagram

Hardness is measured by pressing a hard indenter into the surface of the test material under a specific force (usually about 2 N), as shown in figure 3. The further the indenter sinks into the material, the softer is the material. The depth or size of the indentation left on the material surface after the indenter is removed is used to determine the hardness. The indentation should be large enough to obtain a bulk measurement of the hardness but small enough that it does not damage the surface finish or act as a stress raiser. The indentations produced by the hardness test are usually 0.1–1 mm wide and less than 0.5 mm deep.

Fracture test

Fracture toughness is an engineering term that describes a material's resistance to cracking. Tough materials take a lot of energy to crack, whereas low toughness materials are susceptible to cracking. Fracture toughness is just as significant as other mechanical qualities like elastic modulus and strength for materials used in airplane structures (Mouritz, 2012). Aerospace materials need high toughness to resist the growth of cracks initiating at damage sites (e.g. corrosion pits, impacted regions) or sites of high stress concentration (e.g. fastener holes, windows, doors and other access points in the aircraft).

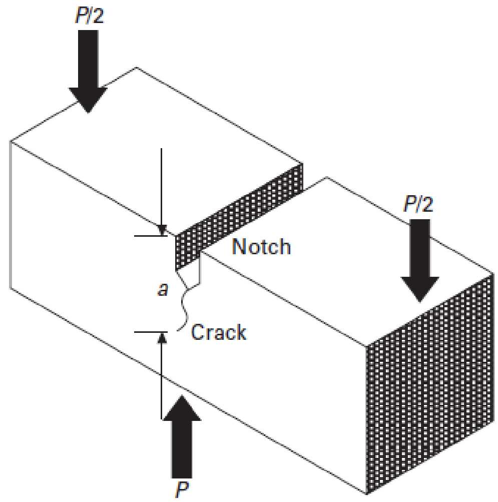

Figure 4. Single-edge notch bend specimen for fracture toughness testing.

There are several test methods to measure fracture toughness, and the most common is the single-edge notch bend (SENB) test. The SENB specimen is a rectangular block of the test material containing a machined notch with a V-shaped tip as shown in figure 4. The notch extends about 50% through the specimen. The SENB test involves applying a three-point load to the specimen to generate a tensile stress at the notch tip. The applied load required to grow a crack from the notch tip through the specimen is used to calculate the fracture toughness. Tough materials require a high load to cause complete fracture of the specimen (Chawla & Meyers, 2003).

Fatigue test

Fatigue tests assess a material's resistance to damage, strength loss, and failure when subjected to cyclic loading. Aerospace materials must be able to sustain repetitive loads for extended periods of time, such as 15 000–20 000 flight hours for current jet engine materials and 80 000–120 000 h for airframe materials. Repeated stress can damage materials, resulting in a loss of strength and, eventually, complete failure. Fatigue tests are used to assess the total number of load cycles before failure and to measure the decline in stiffness and strength of materials under repeated loading.

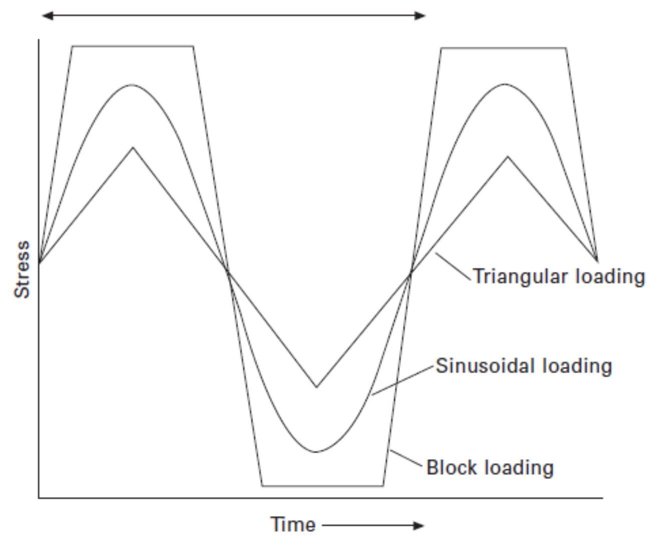

Figure 5. Examples of fatigue loading waveforms

Fatigue tests are performed by repeated tension–tension, compression– compression, tension–compression or other combinations of cyclic loading. The fatigue stress is applied repeatedly to the specimen using a variety of load waveforms, as shown in figure 5. The shape of the loading wave is usually sinusoidal, although triangular and block loads are also used. The frequency of the load cycles is generally low, typically 1–20 Hz (i.e. load cycles per second), to avoid heating of the specimen, which can affect the fatigue results (Mouritz, 2012).

Environmental durability testing

Corrosion is one of the most damaging environmental effects on aerospace materials. In metal alloys, corrosion occurs in many forms which include general corrosion, stress corrosion, pitting corrosion, crevice corrosion and exfoliation corrosion. However, unlike the tests mentioned above, there is no single test that effectively measures the resistance of metals to corrosion. Instead, there are a variety of tests to measure the resistance of metals to different types of corrosion. These tests are usually performed under extreme conditions to accelerate the corrosion rate and thereby determine the long-term corrosion performance of metals.

The selection of corrosion tests for metals used in aircraft should be based on the types of corrosion and corrosive environments most likely to be experienced in service. An example of a test used to measure the corrosion rate of aircraft metals is the salt spray test. This test involves exposing metal specimens to a dense saline fog within a closed chamber. The fog is produced by producing a fine mist of salted solution (usually water containing sodium chloride to replicate seawater). The appearance of corrosion products and damage on the specimen is evaluated after a period of time. Mechanical tests can be performed on the specimen after testing to determine whether the corrosion affected the strength and fatigue properties (Mouritz, 2012).

Mechanism

Although it is important to properly design an aircraft wing, a perfectly designed wing is still no better than the materials it is made of. The risk of material failure of an aircraft wing is largely influenced by the poor selection of the materials of construction. Alloys of aluminum have become the standard material in the aerospace industry for aircraft parts like wings since about 1930 (Starke & Staley, 1996). Pure aluminum does not corrode, but it’s not strong enough to be used anywhere in a wing. Thus, only alloys of aluminum can be used however material failure is always a constant threat. Failure analysis conducted by Stamoulis et al. (2016) revealed that corrosion and fatigue as the principal failure modes, synergistically acting on these wing components.

1. Corrosion

A most important limitation in the selection of materials for aircraft structures, such as aircraft wings, is imposed by the necessity for the materials to resist detrimental chemical reactions with the environment in which they must operate. All of these chemical reactions are collectively referred to as corrosion. Corrosion is essentially an electrochemical process which is characterized by chemical degradation of metals as a result of a reaction with the environment. In a study conducted by Campbell and Lahey (1983), corrosion is one of the primary fatigue initiation sites observed in aircraft. It ranked 5th in the highest number of accidents involving fixed wing and rotary wing with total accidents of 43 and 19, respectively.

Corrosion posed a serious threat in aluminum alloyed wings because aluminum and its alloys readily oxidize, including when Al is present either in solid solution or in intermetallic (IM) particles (Zhou et al., 2012). Different forms of corrosion can attack aluminum alloyed aircraft wings including uniform corrosion, pitting corrosion, crevice corrosion and stress corrosion (Findlay & Harrison, 2002; Grover, 1966).

1.1.Uniform Corrosion

Causes

Also known as uniform attack, as its name suggests, is corrosion that occurs without appreciable localized attack, resulting in uniform thinning. In a microscopic sense, the oxidation and reduction reactions occur randomly over the surface (Callister et al., 2001). In aircraft, uniform corrosion typically occurs in areas where a protective coating that was applied has been damaged or completely destroyed.

This is most commonly experienced by components exposed to outside surfaces such as aircraft wings because they are susceptible to sand, salt and other particulate content in the air which acts as an extremely abrasive medium that can scrape the coating off exposed surface with relative ease (Pavlovic, 2017). From the National Bureau of Standards Report by Ballard (1968), shown in Figure 6 is a fractography of the outside surface of a 7178-T6 aluminum failed wing plank exhibiting uniform corrosion.

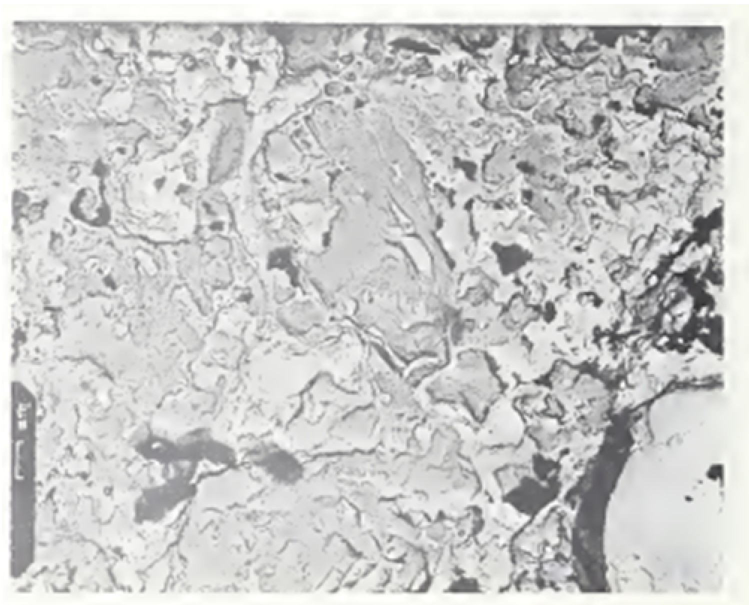

Figure 6. Uniform Corrosion of a 7178-T6 aluminum failed wing plank (Ballard, 1968)

Prevention

Although uniform corrosion is one of the less dangerous types that can occur in aircraft, if left unattended or undetected it can severely reduce the cross-section of the corroded part and thus, greatly impact structural integrity. Pavlovic (2017) suggested some methods to prevent uniform corrosion in aircraft wings discussed below.

Knowing that water and humidity are unavoidable elements for aircraft wings, one of the methods of prevention is the application of surface treatments. Surface treatments, such as galvanizing, can be used, as well as coating with protective paint (Grover, 1966). If weight and situation allow (or require) it, a protective plating can also be included. Specific to aluminum alloyed aircraft wings, for high-strength aluminum alloys, a thin layer of pure aluminum is often applied as a coating to improve the anti-corrosive properties of these alloys.

Replacement of a higher corrosion resistant aluminum alloy is another option. For instance, 7150-T651 aluminum plates on upper wings have been replaced by 7055-T7751 plates in Boeing aircraft. Alloy 7050 has high corrosion resistance and maintains strength in wide sections, making it more resistant to fractures than other alloys. Thus, it is commonly used in wing skins and fuselage, especially in military aircraft (Smye, 2018).

Another method involves the use of sealants. Two types of sealants are used in aircraft: poly-sealants and silicone sealants. Poly-sealants (e.g., polysulfide, polythioether, and polyurethane) are all two-component compounds where mixing the base and a curing agent creates a rubbery solid. Silicone sealants, on the other hand, have only one component, and they solidify when exposed to moisture in the air. The main purpose of sealants in aircraft is to isolate pressurized areas and prevent water, moisture, dust, salt and aircraft fluids from intruding into areas where they can cause corrosion.

1.2. Pitting Corrosion

Causes

Pitting occurs when some areas corrode faster than others. It is a form of very localized corrosion attack characterized by the formation of small pits or holes. It is one of the most destructive and intense forms of corrosion. The mechanism for pitting is probably the same as for crevice corrosion in that oxidation occurs within the pit itself, with complementary reduction at the surface. While a pit may start as a result of some surface imperfection, most severe pitting is normally associated with environmental reactions (Callister et al., 2001; Grover, 1966). For aluminum alloyed wings, corrosion of aluminum in the passive range is localized, usually manifested by random formation of pits. The damage evolution law of pitting stage (corrosion pits) of 7075 ultra-high-strength aluminum alloy—which is commonly used for aircraft wing panel, wing beam, wing rib, and fuselage—was mainly studied by Gao et al. (2020) and the corrosion cycle is shown in Figure 7.

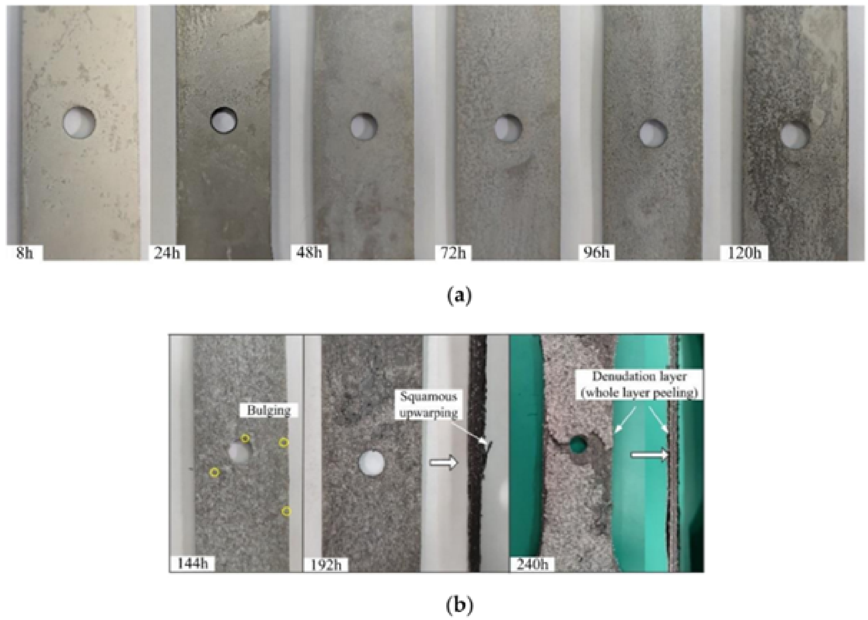

Figure 7. Corrosion morphology of 7075 ultra-high-strength aluminum alloy. (a) *Pitting*, (b) *Denudation* (Gao et al., 2020).

Prevention

The most effective preventive action to avoid pitting corrosion damage is selecting materials with the appropriate pitting corrosion resistance as required for the service conditions. In addition, providing a corrosion-resistant coating or cathodic protection may be necessary in some cases. Surface treatments such as coating or anodizing as well as keeping the aluminum alloy surfaces clean can also minimize the pitting corrosion damage for aluminum alloyed aircraft wings (Prabhu, 2019).

1.3.Crevice Corrosion

Causes

Crevice corrosion occurs when localized changes in the corrosive environment exist and lead to accelerated localized attack. These changes in the localized corrosive environment are generated by the existence of narrow crevices that contain a stagnant environment, which results in a difference in concentration of the cathode reactant between the crevice region and the external surface of the material. Crevices can be formed at joints between two materials, e.g. riveted, threaded, or welded structures, contact of a metal with a nonmetallic material, or a deposit of debris on the metal surface. This is commonly seen in aircraft wings; these components are directly attached to the main body of the aircraft, creating joints that are susceptible to crevice corrosion. Skin corrosion on the upper wing surfaces of rib stiffened aircraft P3C (Orion) aircraft wing is shown in Figure 8. At the rivets, crevice corrosion occurs (Matthews & Peng, 2018).

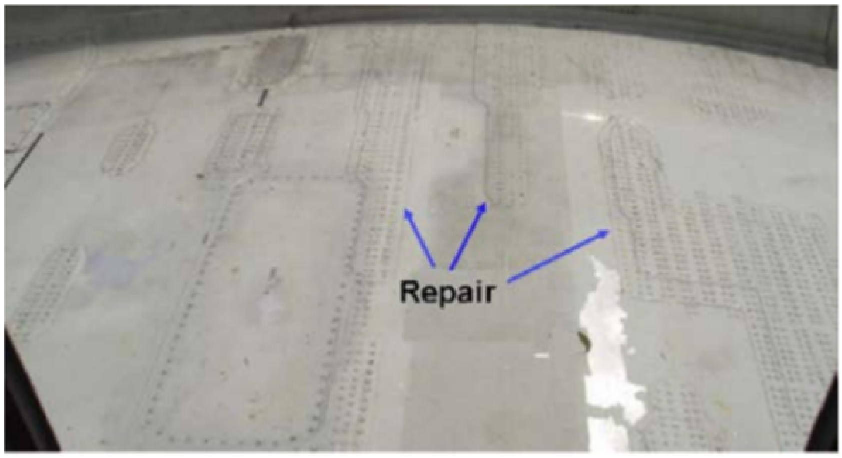

Figure 8. Multiple corrosion repairs on a P3C aircraft wing made of 7075 aluminum alloy (Matthews & Peng, 2018).

Prevention

One of the ways of minimizing crevice corrosion at the joints is by sealing the gaps on the joint surfaces with a polysulfide sealant. The sealant is used in skin-to-stringer as well as skin-to-shear types of joints in the fuselage, areas of skin doublers, chord-to-skin joints for the wing and wheel structure, etc. In cases of severe proneness to corrosion, such as electrical bonds and antenna peripheries, fillet seals are used (Prabhu, 2020).

1.4.Stress Corrosion

Causes

A combination of steady tensile stress (applied or residual or both) and a corrosive environment may lead to mechanical-environmental failure called stress-corrosion cracking (Findlay & Harrison, 2002; Grover, 1966). Failure by stress corrosion cracking is frequently caused by simultaneous exposure to an apparently mild chemical environment and to a tensile stress well below the yield strength of the material. The stress required for failure can originate from in-service conditions or from residual stress during component manufacturing.

Stress corrosion cracking (SCC) is considered to be the bane of aluminum alloys. Stress corrosion occurs rapidly and becomes destructive in aluminum alloyed wings because it follows the grain boundaries of alloys of aluminum (Prabhu, 2020). SCC requires three simultaneous conditions: (1) a susceptible alloy; (2) a humid or water environment; and (3) a tensile stress which will open the crack and enable crack propagation. SCC can occur in two modes: intergranular stress corrosion cracking (IGSCC) which is the more common form, or transgranular SCC (TGSCC). In IGSCC, the crack follows the grain boundaries. In transgranular stress corrosion cracking (TGSCC), the cracks cut through the grains and are oblivious to the grain boundaries.

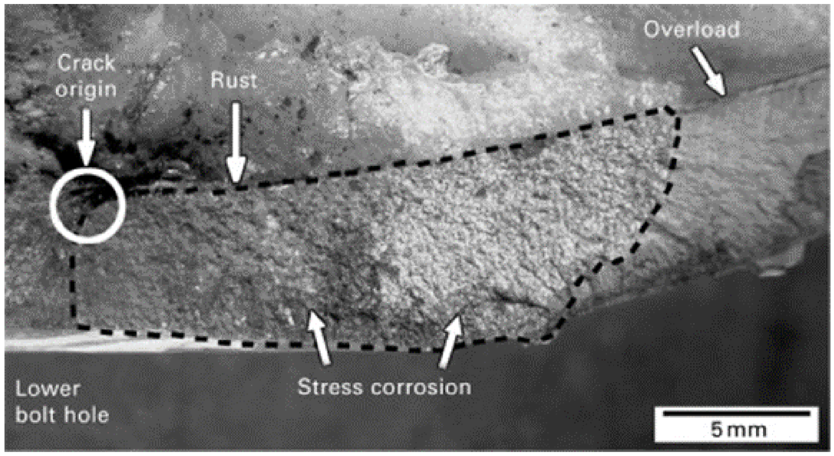

Figure 9. Stress Corrosion in an Aircraft (Wanhill et al., 2011)

Prevention

To minimize the hazards of stress corrosion, corrective practices such as stress-relieving heat treatments, optimum grain flow orientation, and shot peening or other surface working may be necessary. Just like the other forms of corrosion, application of protective coatings can also reduce the chances of this type of corrosion.

For aluminum alloyed aircraft wings, choosing lower strength alloys over higher strength alloys is favorable to prevent stress corrosion cracking. In the 1950s, the general trend was to use higher strength alloys (e.g., 7178-T651 used on the Boeing 707) but the industry changed to using lower strength alloys. The yield strength of the upper wing skin did not exceed the 1950 level until the Boeing 777 in the 1990s. The reason lower strength alloys were selected for the Boeing 747 and the L-1011 was that the aircraft designers chose an alloy with better SCC resistance rather than the higher yield strength (Total Materia, 2008).

2. Fatigue

Causes

Fatigue is a process whereby cracking occurs under the influence of repeated or cyclic stresses, which are normally substantially below the nominal yield strength of the material. Components that fail by fatigue usually undergo three separate stages of crack growth, which are described as follows:

· Initiation of a fatigue crack. This can be influenced by stress concentrations such as material defects or design.

· Propagation of the fatigue crack. This is progressive cyclic growth of the crack.

· Final sudden failure. Eventually, the propagating crack reaches a critical size at which the remaining material cannot support the applied loads and sudden rupture occurs.

For aircraft wings, pressure is the main cause of weakened metal components. Due to outside exposure from straight-and-level flight, turning, accelerating, decelerating and other maneuvers, it creates repeated changes in the loading of the wings and other surfaces. In addition, with the regular pressurization and depressurization of flying at high altitudes, the metal skin of an aircraft wing expands and contracts. Each cycle begins at the time of lift-off and ends after landing.

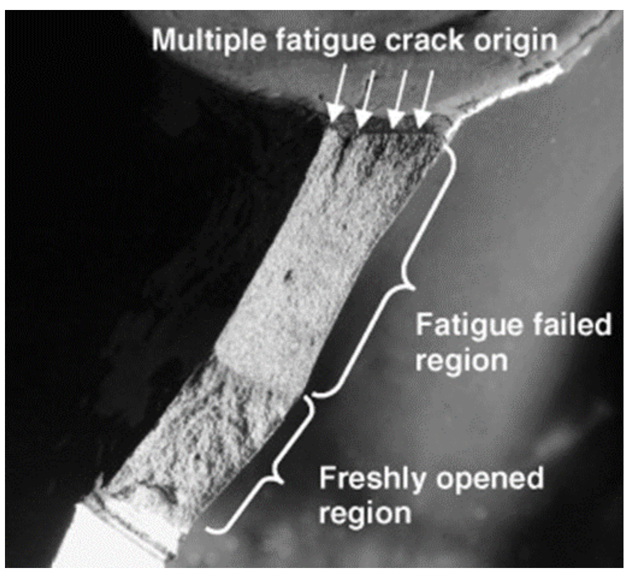

Figure 10. Fatigue failure of aircraft components (Bhaumik et al., 2008)

Prevention

There are two general principles for minimizing the hazard of fatigue: surface protection and stress minimization (Grover, 1966). The first is to protect against corrosion in any anticipated environment. All the techniques of the corrosion expert can be utilized, such as proper choice of materials, coatings and surface protection, and separation of electrochemically dissimilar metals. Polishing the surface is also a good idea. Polished surfaces can fend off the effects of fatigue better than those left unpolished. It also buffs out any existing surface damage. When metal elements of an aircraft wing are manufactured, micro-defects—such as pits, scratches and small gouges—can be left on their surfaces. These tiny inconsistencies can facilitate corrosion and worsen with the pressures of flight. Surfaces that are ground and polished with care will be rid of these weaknesses, eliminating the risk of expanding and causing failure. However, this will not eliminate imperfections within the metal, so regular testing is still required.

The second principle is to keep tension stresses, including residual stress, low. A wing must be allowed to twist and bend during the stresses encountered in flight. For instance, the wing tips of a B 52 flex up and down twelve feet during routine flights.

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