Life and Failure of Aircraft Wheels – A Review

Benjamin Rohit1,*，Punya D Gowda1，Nandini B Nagaraju1 and Meghana S 1

1Department of Aerospace Engineering, Rashtreeya Vidyalaya College of Engineering

*e-mail: benjaminrohit25@gmail.com

Abstract. Aircraft wheels mounted with tires support the entire weight of an aircraft during ground operations and landing. Very stringent demands are placed on performance and reliability of landing gear components. The present day wheel is a split type forged aluminium alloy with an internal cold mounted bearing and the brake design energies have increased two fold over the last few decades. The check up for integrity of aircraft wheels are carried out using various techniques by trained and competent personals at regular inspection intervals. From literature we can see that most failures of aircraft rims have been due to high cycle fatigue. Corrosion has played a significant role in fatigue crack nucleation. Braking and high landing loads contribute to the fatigue crack growth. Aircraft’s vertical velocity, runway friction coefficient and the asphalts elastic modulus play a significant role in the crack propagation in aircraft wheels. Pitting also serves as a site for stress concentration and hence, nucleation of fatigue cracks. Over-inflation or under-inflation can cause an increase in the stress levels on aircraft wheels.

The present review critically analyses the published work on the fatigue fracture of aircraft wheel rim, current inspection techniques to detect fatigue crack nucleation and growth.

1. Introduction

Wheels and tires of the modern day aircraft are among the most highly stressed parts. Impact loads, cyclic loads, corrosion, and burn outs can contribute to the failure of the landing gear wheels. Failure of wheels could lead to multiple fragments being thrust out, this could pose a great safety threat to maintenance personal or the entire aircraft itself. An aircraft wheel is designed to be able to accommodate the selected tire, to house the brakes and have a long life and minimum weight while accomplishing the above tasks. Manufacturers of this equipment need to adopt a cost conservative design. It has been demonstrated over the past that cost analysis for aircraft wheels and tires needs to be performed based on number of landings than based on the number of flying hours [1].

Forged aluminium alloy is still the most preferred over other alloys of magnesium and steel due to its lower weight and resistance to corrosion. Titanium alloy wheels can be used if the operator would accept the higher initial cost involved. And with the complexity of forging titanium with the required precision the initial cost could be 10 times higher than that of forged aluminium [1]. Aircraft wheels generally are of two piece type construction to be able to accommodate the very stiff tires that were designed. Wheels need to be tested as per FAA standard for aircraft wheels (TSO-C26c). The wheels are tested to withstand radial loads, axial loads and the combination of both. The wheels also are tested to roll a predefined distance under load and there must be no cracks after the test is completed.
An FAA study in 1985 concluded that over 30% of 5000 failures reported from 1970 to 1975 were due to wheel problems which did not include the removal of wheels ahead of the service life of the wheel. Fatigue cracks and corrosion are expected as the aircraft progresses through its service life. Corrosion and fatigue cracks could affect the airworthiness of the aircraft. Aircraft wheels are subjected to periodical tests to detect cracks, the most frequently used techniques are non-destructive techniques. Radiography, eddy currents, ultrasound, and penetrants are a few techniques used by very well-trained personal to detect cracks. Eddy current method is the most frequently used method considering the cost and accessibility.

If a crack is detected in a part, it must be repaired or replaced immediately [6]. If a discrepancy is found while the wheel is still mounted on the aircraft, further detailed investigation may be required by removing the wheel from the aircraft.

1.1 Case studies on wheel and tire failures in the past
There have been incidents in the past where the wheel (flange or assembly) or the tire have failed. Wheel failures have occurred due to poor NDT (Non-Destructive Test) techniques, incorrect installation, fatigue and insufficient lubrication or contamination. In many such situations there have been injuries to maintenance and service personal. This section attempts to cover previously failed wheel and tires and the reason to failure. Table 1 gives the summary of case histories of aircraft wheel failures.

| Sl No | Aircraft     | Failure Mechanism                              | Part               | Error                                                                 |
|-------|--------------|------------------------------------------------|--------------------|----------------------------------------------------------------------|
| 1     | Lockheed C-130 | High cycle fatigue caused the initiation and growth of the crack | Wheel Flange       | NDT could not detect crack during initiation [2].                      |
| 2     | Piaggio Avanti 180 | Corrosion pitting lead to the failure of the inner flange | Wheel Flange       | Fretting between tire bead and tube well damaged the protective coating hence, causing corrosion [3]. |
| 3     | Boeing 737   | Fatigue crack initiation at the bore leading to crack growth and catastrophic failure | Inboard Wheel      | Stress concentration between the bore and circumferential radius [4]. |
| 4     | Boeing 737-500 | Overheating and fire at the wheel hub caused by the failure of the outboard bearing | Wheel hub and bearing | Incorrect installation of the bearing, insufficient lubrication and the presence of water or contamination could have caused the failure [5]. |

2. Aircraft Wheel
Manufacturers of aircraft demand long wheel life capability in terms of roll miles and number of landings/take-offs. Aircraft wheels have two basic configurations, the A-frame and bowl type. Improvement in anti-skid control and greater flexibility in landing gear struts have increased the requirements of the aircraft wheel.

Fatigue failure of the wheel could occur irrespective on the position whether it be the inboard or the outboard half of the wheel assembly. Wheel assembly failures generally occur soon after a tire gets replaced on the wheel and the aircraft is back into service [7].

Aircraft wheels are designed for fail-safe, the point where the tubewell meets the wheel web is generally designed to exhibit low fatigue life and thus behave as a fail-safe point. The fail-safe point is schematically shown in figure 1. A crack which nucleates and grows at this fail-safe point will allow...
the tire to deflate and this can be detected during a pre-flight inspection [8]. A few reasons for failure of wheel hub are reviewed in this section.

![Cross section view of the two piece type aircraft wheel found on modern airliners](image)

Figure 1. Cross section view of the two piece type aircraft wheel found on modern airliners

2.1 Factors causing crack nucleation in wheel hub

Aircraft wheels are the most susceptible to corrosion than other parts due to the exposure to water and dust. Due to low corrosion fatigue strength of aluminium alloys, corrosion can lead to catastrophic failure. Contact with Airfield pavement de-icing products (PDPs) increase the probability of corrosion in aircraft wheels.

Corrosion pitting is one of the preferred sites for crack nucleation. Corrosion Pitting could also lead to increase in stress concentration and hence acts as a fatigue crack nucleation site. Pitting can be caused as a result of mechanical factors, increased temperatures and surrounding environment [9]. Corrosion pitting could occur even though the wheel is anodized, corrosion could be present before the anodizing process. Corrosion likely forms when the wheel is dipped in a bath during the pre-anodizing process [10].

Corrosion in wheel bearing has been reported in stored aircraft also and the grease used for lubrication played an important role in corrosion protection. It was concluded by an experiment by the US Navy that greases with high alkalinity, good balance of water resistance and water emulsification, resistance to hardening during use and high viscosity greases were good for use of corrosion protection of wheel bearings [11]. The use of the right kind of grease could have prevented the failure of a Boeing 737-500 mentioned in table 1.

Apart from stress concentrations developed from corrosion, stress concentrations could develop at the sharp corners of the fastener hole undercut which is provided for the gear attachment and this stress concentration could lead to a crack nucleation and radial growth of the nucleated crack growth under fatigue loading [12].

Aircraft wheel could also fail due to nut and bolt failure. The nut could fail due to inherent crack or a crack could have applied when it was over torqued during installation or an overload during landing. In some cases the nut gets weakened due to hydrogen effects during the cadmium coating process. Hydrogen embrittlement could occur when cadmium coating is done through electro-deposition plating to protect the component against corrosion. Hydrogen gets attracted to grain boundaries and weakens the grain boundaries. A higher value of stress is required for hydrogen cracking to occur called the static fatigue limit. Failure could when this limit is reached when the nut is either over torqued or when high landing loads are experienced [7]. The lack of cadmium re-plating to the tie bolts could also initiate corrosion fatigue and lead to failure as in the case of a Boeing 737-400 in October 2008[13]. Wheel bead seat and flange are also typical regions for crack initiation due high bending.
stresses and during ground operations stresses peak up as the ground to tire loads are transmitted to the wheel through the wheel tire interface this could provide enough driving force to propagate the crack [10]. When tire seat is fitted against the rim this prohibits the crack from leaking the pressurized gas and thus the crack may grow to critical lengths without being detected. Due to the nonlinear behaviour of the tire, it is also not easy to determine the pressure distribution on the wheel.

2.2 Crack Growth
The nucleated crack could grow as a result of repetitive loading during ground manoeuvres. Braking shortly after landing is one of favourable reason for crack growth. Landing impact stresses also play a significant role in crack growth. In spite of aircraft operators increasing the frequency of inspection to detect defects early catastrophic failures have occurred as the fatigue cracks could not be detected in the early stage [14]. As the cyclic loads on the wheels are applied during ground operations the rate of crack growth is sensitive to the take-off weight of the aircraft. Tire pressure has a strong influence on endurance of the wheel, higher inflation pressure can reduce the life of the wheel by 75% [14].

2.3 Inspection of Wheels during service
All aircraft wheels are inspected for manufacture defects to ensure defect free product before supply. Inspection during the service life of the aircraft wheel is also important. Inspection of the wheel is necessary to detect cracks that could lead to catastrophic failure. Crack detection by NDT is influenced by a few factors such as NDT method, material, configuration, inspector’s proficiency and environment.

Location of the cracks plays a vital role in detection by NDT techniques during routine inspection. Locations where the inspection can be conducted without removal of the tire can be conducted as a routine inspection, but few locations such as the tubewell bead seat, flange locations etc. cannot be inspected without the removal of the tire. Cracks developing at the tubewell could be detected during the pre-flight inspection, as a crack in the tubewell will deflate the tire and this can be visually inspected during pre-flight inspection. Crack which have developed in the bead seat and flange regions can only be detected during a tire change.

2.3.1 NDT techniques A few NDT techniques used to detect crack are reviewed in this section. NDT techniques such as the dye penetrant test, eddy current, Ultrasonic and radiography are the commonly used techniques to detect crack during inspection of the wheel hub. It is observed that NDT techniques are highly influenced by configuration of the part, corrosion material, crack location, orientation and tightness. Though the initial investment is high for ultrasonic and eddy current equipment, subsequent inspections are economical. Dye penetrant test is considered to be the most economical of all the NDT tests. But eddy current test is the most widely used technique to detect cracks in aircraft wheels.

Dye penetrant, eddy current and ultrasonic test techniques are not preferable to detect crack with radial lengths less than 2.5mm [15]. Eddy currents are preferable to detect tight cracks where visual, ultrasonic and dye penetrant may fail. Eddy current tests are done around the bead seat area, bolt holes, and the mating surfaces of wheel hubs [16].

Magnetic particle test can only be done on ferrous materials. Tie bolts are tested for cracks by the method of magnetic particle test. Ultrasonic tests can detect cracks through the thickness and can extent through the shot peening region into the susceptible region.

2.4 Aircraft Wheels
While striving to develop the wheel to meet new requirements the cost effectiveness also needs to be considered along with safety requirements. Being very conserved while designing the wheel could add to the cost and also the weight of the wheel. It is a continuous challenge to produce the lightest possible wheel which would meet all the safety requirements at the least cost. Two most important factors to minimize wheel failures are design, test procedures to represent the actual operating conditions and inspection of the wheels. There could be an increase in 10 to 15% of the cost if a
certified wheel were to develop a structural problem. Redesigning the wheel, changing forging and retest could be factors that could add to the increase in cost [15]. Additional to the cost due to the change in design, a failed wheel could damage tires and aircraft parts and add to the cost.

The primary wheel cost is generally due to the depletion in fatigue life of the wheel and the timely retirement of the wheel. By controlling corrosion and timely replacement of worn parts can reduce the cost by extending the useful life of aircraft wheels. Careful measures in handling the wheel while storing and transportation could also add to the reduction in cost.

2.4.1 Inspection Cost NDT techniques are commonly used to inspect wheels of aircraft for corrosion and cracks and also for keeping the inspection costs low. A complete check of an aircraft can be a very costly and also takes over a month, and such tests cannot be performed on very short intervals as done on the aircraft wheels.

3. Summary
1. Corrosion, Nut over-torquing, Hydrogen embrittlement and bolt failures lead to reduction in life of aircraft wheels, and corrosion plays a major role in the fatigue life reduction of aircraft wheels.
2. Corrosion on aircraft wheels is caused due to pavement deicing products (PDP), increased temperatures in tires and during braking, pre-anodizing process, quality of grease used etc. Using the prescribed methods aircraft wheels can be protected from corrosion.
3. Braking force, landing impact and tire inflation pressure can affect the crack growth rate in aircraft wheels.
4. Eddy current tests, Dye penetrant and Ultrasonic tests are the most used NDT techniques to check for cracks on aircraft wheels, where dye penetrant test is the most economical and eddy current the most reliable.

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