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Fracture/Fatigue Failures of Products and Components In-Service

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Abstract

This report presents a materials failure analysis of an in-service Boeing 737 next generation main landing gear wheel hub, a safety critical aluminium alloy component (typically AA7075-T6), that failed due to high-cycle fatigue. The investigation identifies fatigue crack initiation at the bearing bore shoulder radius, a region of high geometric stress concentration, followed by progressive crack growth (characterised by beach marks and multiple axial/circumferential cracks), and final ductile overload fracture, evidenced by a rough, fibrous surface with micro void coalescence.

Fractographic examination (macroscopic and microscopic), fluorescent penetrant inspection (revealing multiple secondary cracks), and fracture mechanics principles (including Paris Law and stress intensity factor analysis), support the conclusion that the failure resulted from the interaction of cyclic radial/thermal loads, multiaxial stresses, incomplete shot peening coverage, and microstructural sensitivities (e.g., intermetallic inclusions). Ashby materials selection charts highlight the strength toughness trade-off inherent in high strength aluminium alloys, explaining their vulnerability to fatigue despite excellent specific strength and stiffness.

The analysis underscores the importance of structure property performance relationships in preventing fatigue failures in aerospace components. Recommendations include full radius shot peening, enhanced volumetric non-destructive testing (e.g., ultrasonic inspection), improved surface finishing, and stricter maintenance protocols to mitigate future occurrences and enhance operational safety.

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1 Introduction

Aircraft wheel bearing assemblies are safety-critical structural components within the landing gear system, responsible for transmitting aircraft weight, braking forces, and dynamic loads generated during landing, taxiing, and take-off. These components operate under severe service conditions, including high cyclic mechanical stresses, thermal loading from braking, and exposure to aggressive environmental conditions. Failure of a wheel bearing assemblies can therefore result in loss of wheel integrity, compromised aircraft controllability, runway debris hazards, and potentially catastrophic safety consequences. As such, wheel bearing assemblies are designed with strict airworthiness requirements and are subject to rigorous inspection and maintenance regimes throughout their service life.

Despite conservative design, fatigue remains a dominant life-limiting mechanism, especially at geometric stress concentrators such as bearing bores and fillet radii. High-strength aluminium alloys commonly used in wheel hubs offer weight and strength advantages but exhibit increased sensitivity to fatigue initiation and crack growth.

This report presents a materials failure analysis of an in-service aircraft wheel bearing assembly or 'wheel hub', fracture associated with a Boeing 737 main landing gear assembly, seen in Figure 1. The investigation focuses on identifying the operative fatigue and fracture mechanisms responsible for the failure, supported by fractographic evidence, theoretical fatigue and fracture mechanics, and relevant materials science principles. Particular attention is given to the influence of material selection, microstructural characteristics, and geometric stress concentrations on crack initiation and growth behaviour.

Through this analysis, the report seeks to demonstrate how an understanding of structure, property, and performance relationships is essential to the prevention of material failure in safety-critical aerospace components.

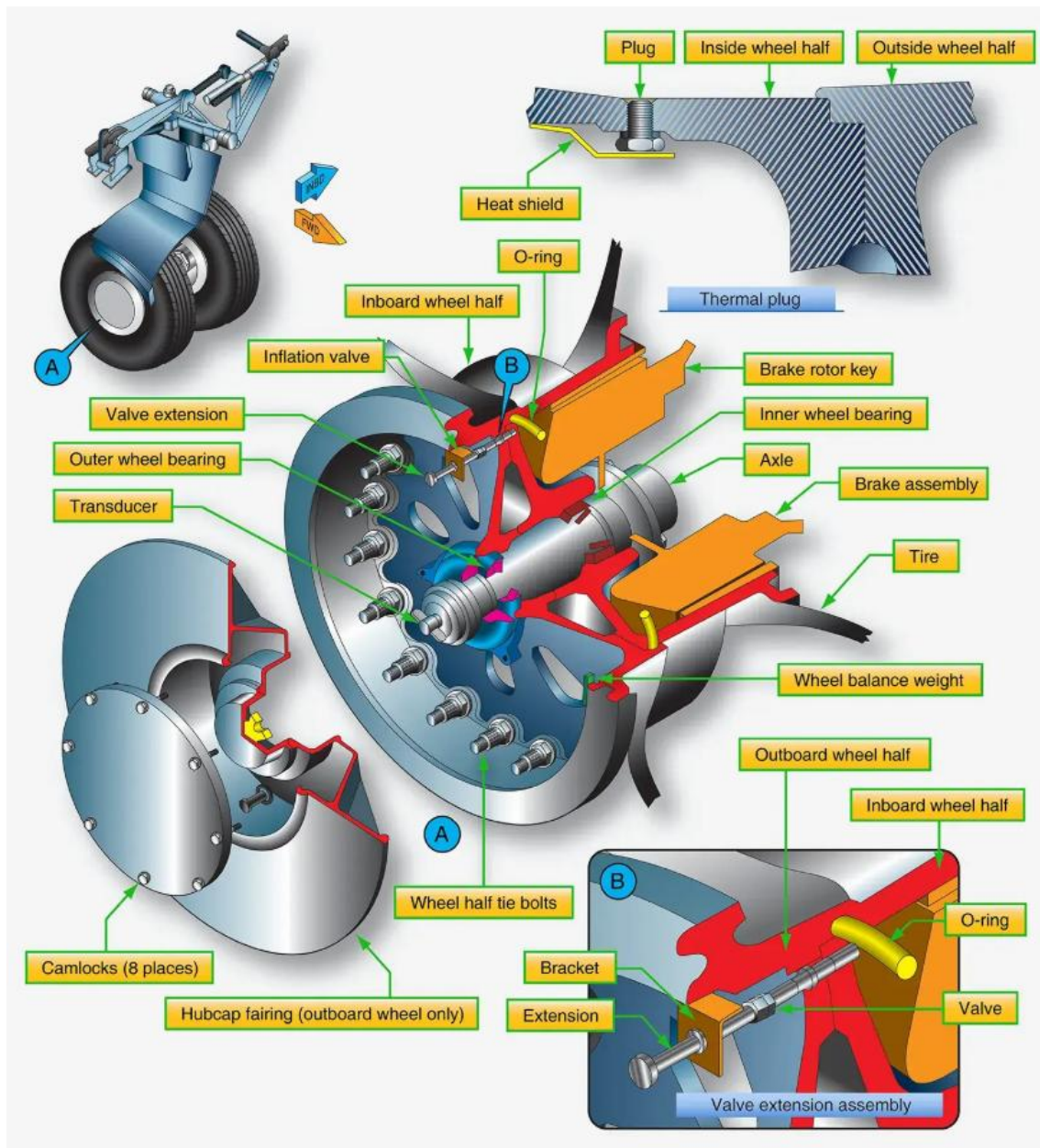


Figure 1 Features of a Two-Piece Aircraft Wheel Assembly [1]

2 Technical Exposition

2.1 Component Selection & Fatigue Theory

The aircraft wheel hub is a safety-critical structural component within the main landing gear assembly, responsible for supporting the aircraft weight, and transmitting braking and ground-handling loads between the wheel and the axle. The wheel hub assembly typically consists of an inboard and outboard half, typically cast or forged from aluminium or magnesium alloy, which are bolted together containing a groove at the mating surfaces for an O-ring, seen in Figure 2. sealing the rim to form a complete hub capable of accommodating the wheel bearings and tyre assembly. This two-piece configuration facilitates assembly, inspection, and maintenance, but also introduces geometric features such as bearing bores, bolt holes, and fillet radii that act as stress concentrated areas [1].

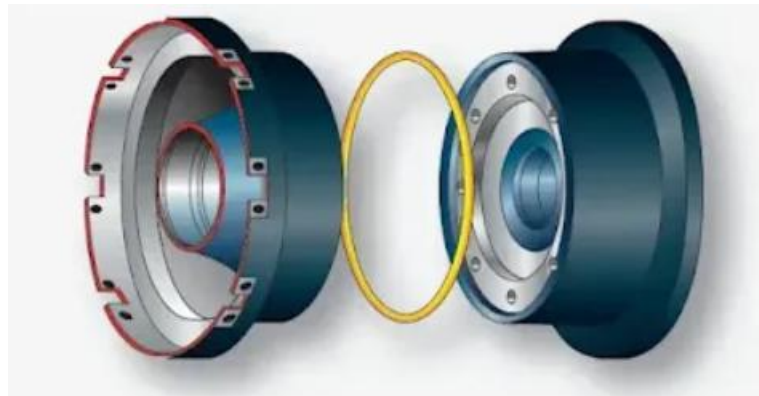


Figure 2 The Assembly Inboard/Outboard Wheel hub & O-Ring [1]

Stress defines the mechanical loading imposed on a component, fatigue represents the progressive accumulation of damage under repeated stress cycles, and fracture is the final failure event that occurs when this accumulated damage reduces the material's remaining capacity below the applied stress. [2]

During service, the wheel hub experiences combined mechanical and thermal loading dominated by cyclic radial stresses from aircraft weight during landing and ground operations. High-magnitude landing loads are superimposed on lower-amplitude taxiing loads, placing the hub primarily in a high-cycle fatigue regime.

Beyond radial loading, braking torque imposes combined shear and bending stresses that are concentrated at bearing bores and geometric transitions, while associated thermal exposure locally degrades material strength and accelerates fatigue damage [2]. Tyre inflation pressure introduces a sustained tensile mean stress, reducing the allowable cyclic stress range for fatigue resistance.

The resulting stress spectrum, dominated by high-cycle taxi loads, intermittent high-magnitude landing and braking loads, and occasional overload events, creates conditions highly conducive to fatigue crack initiation and growth at critical stress concentrators, particularly the bearing bore radius.

2.2 Strength, Toughness & Hardness Trade-offs

Strong materials like aluminium (AA7075-T6) are great for carrying loads, but they usually trade off some toughness (ability to absorb energy without breaking suddenly) and hardness (resistance to dents/scratches).

Ashby chart in Figure 3 shows:

- Very strong metals can be less tough, so cracks spread faster once started.
- The wheel hub needs high strength for weight savings, but this makes it more prone to fatigue cracks at weak spots.

This inherent balance between strength, toughness, and hardness means that even small surface imperfections can dramatically elevate local stress intensity,

making high-quality surface finishes essential for delaying fatigue crack initiation in components of this class.

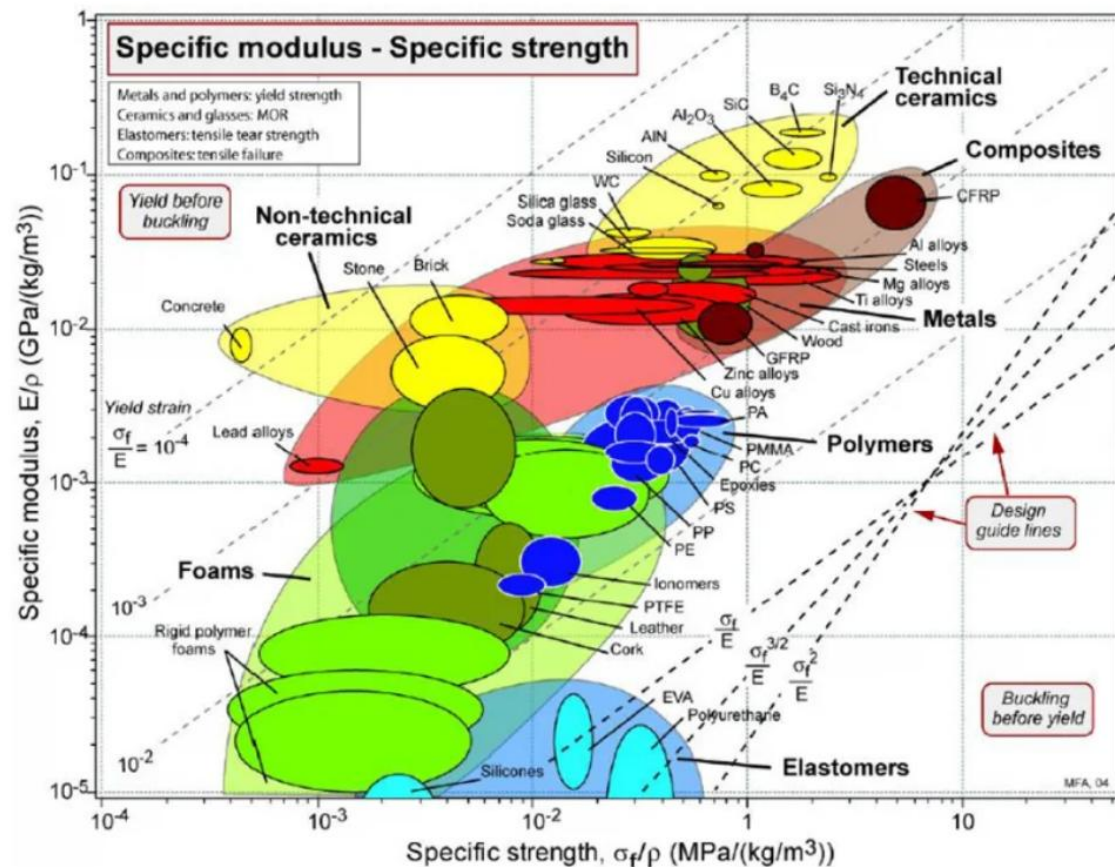


Figure 3 Ashby Chart Specific Modulus Vs Specific Strength [3]

2.3 Influence of Stress Concentration on Surface Defects and Design

Aircraft wheels are made of two different sized halves, the inner half is larger because it contains the parts needed to drive the brake rotor and often houses safety features like thermal plugs or over-inflation plugs, seen in Figure 4. These thermal plugs melt if the brakes overheat, releasing air from the tire to prevent a pressurised explosion, after which the wheel and nearby assemblies must be inspected [1]. The outer wheel half simply bolts on, holds the outer bearing, carry sensors or a hub cap, and provides access for inflating the tire.

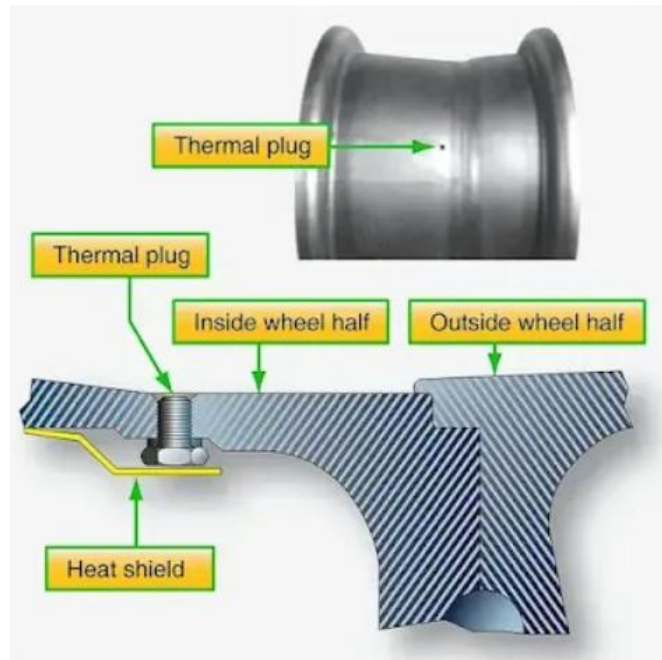


Figure 4 Thermal Plug Safety Feature [1]

When manufacturing the components, sharp corners create areas of high stress concentration, which can lead to part failure or reduced durability. The stress concentration factor is particularly high when the radius-to-thickness (R/T) ratio is less than 0.5, seen in Figure 5. This concentration of stress can significantly weaken the part, especially under load or impact [4].

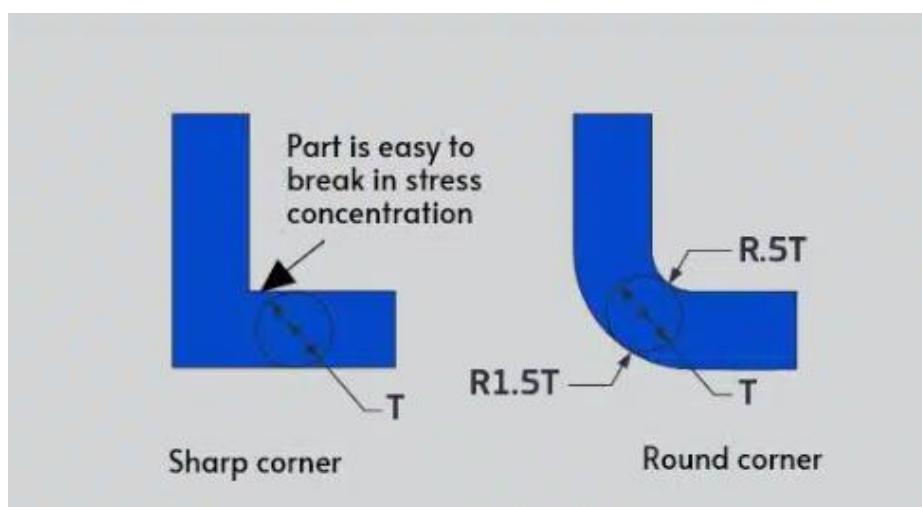


Figure 5 Fillet Radii Vs Corner Radii [4]

Severe mechanical, thermal, and environmental conditions experienced by aircraft landing gear assemblies, rigorous inspection, correct installation, and ongoing maintenance are essential; failure to maintain these systems to prescribed standards significantly increases the risk of undetected damage accumulation, accelerated fatigue crack growth, and ultimately catastrophic failure.

Correct axle nut torque is essential for safe wheel operation. Under-torquing can allow excessive bearing movement '**scalloping**', seen in Figure 6, leading to abnormal contact stresses and accelerated damage within the wheel hub, while over-torquing restricts bearing load distribution and lubrication, increasing friction and heat generation.



Figure 6 Scalloping, Eventually Leads to Wheel Bearing Failure [1]

Several other bearing damage conditions are considered unacceptable for continued service due to their impact on load transfer and fatigue performance.



Figure 7 Galling, Mechanical Wear Leads to Surface Tearing [1]

Galling, seen in Figure 7, arises from severe adhesive wear between contacting surfaces, typically caused by insufficient lubrication or excessive contact stress. Localised frictional heating can result in micro-welding at asperity junctions, which are subsequently torn apart during relative motion, leading to significant surface material loss aligned with the direction of sliding [1].



Figure 8 Spalling, Sub-surface Cracks Leads to Surface Fatigue [1]

Spalling, seen in Figure 8, is characterised by the detachment of small fragments from the hardened surface of bearing rollers or raceways. This form of surface fatigue is driven by repeated cyclic contact stresses and indicates subsurface crack initiation and propagation. Once spalling is present, stress redistribution and debris generation accelerate bearing degradation.

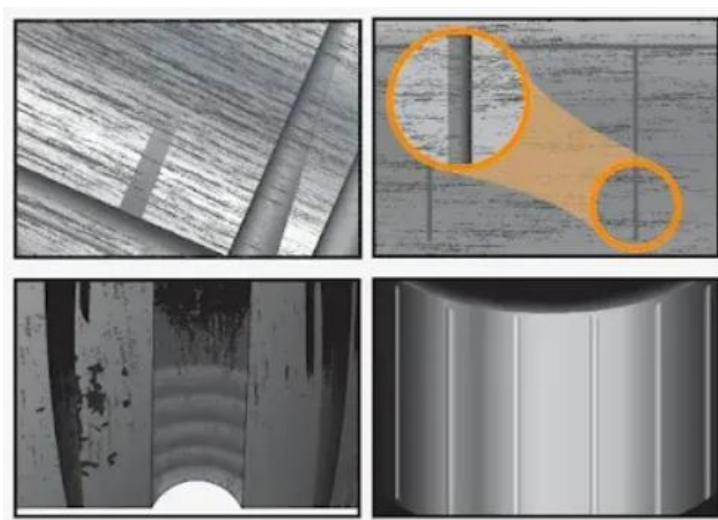


Figure 9 Brinelling, Excessive Load Leads to Mechanical Indentation Failure [1]

Brinelling, seen in Figure 9, refers to permanent indentations formed in bearing raceways due to excessive static or impact loading. Such indentations disrupt smooth rolling motion, generating vibration and stress concentrations that promote early fatigue failure. Brinelling is frequently linked to improper installation, handling, or severe operational impacts.

Consideration of these bearing damage mechanisms provides contextual understanding of the bearing-hub load transfer behaviour and the range of degradation processes that may influence fatigue performance in aircraft wheel assemblies.

2.4 Fracture Characteristics of Fatigue Failure

Fatigue fracture surfaces exhibit distinct macroscopic and microscopic characteristics that, when examined together, provide insight into crack initiation, propagation behaviour, and the transition to final failure.

2.4.1 Macroscopic Fatigue Features

Macroscopic features, seen in Figure 10, are those visible to the unaided eye or low magnification. In fatigue failures, these features describe the overall behaviour of the crack over time and its relationship to component geometry and loading [5].

Typical macroscopic fatigue features include:

- Crack origin location, often associated with stress concentrations such as fillet radii, holes, or surface defects
- Beach marks, which appear as concentric or semi-circular patterns and indicate changes in crack growth rate due to variable loading or service interruptions
- Multiple crack fronts, suggesting distributed stress or secondary initiation sites
- Final overload region, often rougher in appearance, indicating rapid fracture once the remaining cross-section can no longer sustain the applied load

Macroscopic analysis is used to determine where the failure initiated, how the crack propagated.

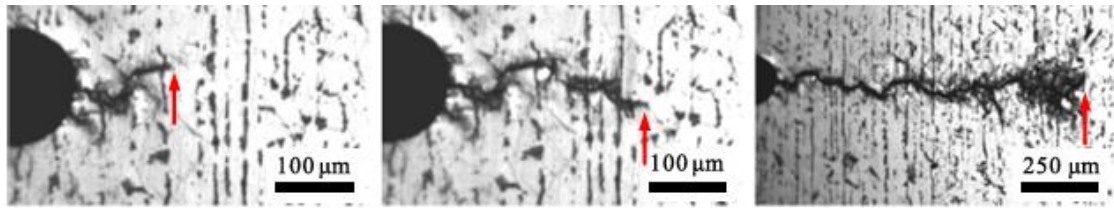


Figure 10 Macroscopy Crack Growth Imaging [5]

2.4.2 Microscopic Fracture Characteristics

Microscopic features, seen in Figure 11, are observed using scanning electron microscopy (SEM) or high-magnification optical techniques and provide insight into the mechanisms operating at the grain and sub-grain level [5].

Typical microscopic fatigue features include:

- Fatigue striations, representing incremental crack advance per loading cycle or group of cycles
- Micro-void coalescence, associated with ductile overload fracture
- Brittle features in some materials
- Crack initiation at inclusions, precipitates, or grain boundaries, revealing microstructural sensitivity
- Slip bands, indicating cyclic plastic deformation at the crack origin

Microscopic analysis explains why the crack initiated and propagated, linking fatigue behaviour to material microstructure, heat treatment, and environmental effects [2].

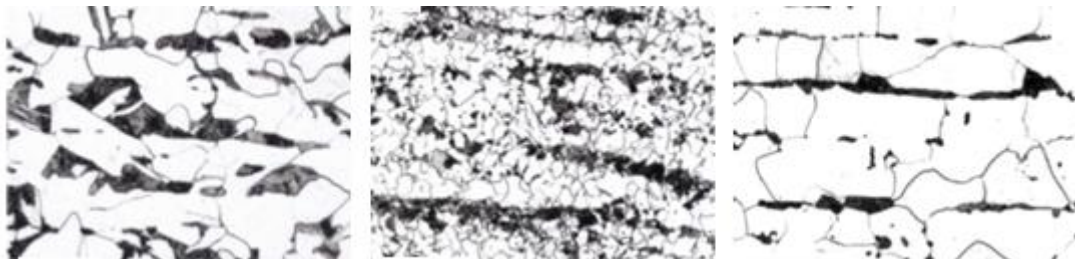


Figure 11 Microscopic Crack Growth Imaging [5]

2.5 Plastic Zone Behaviour

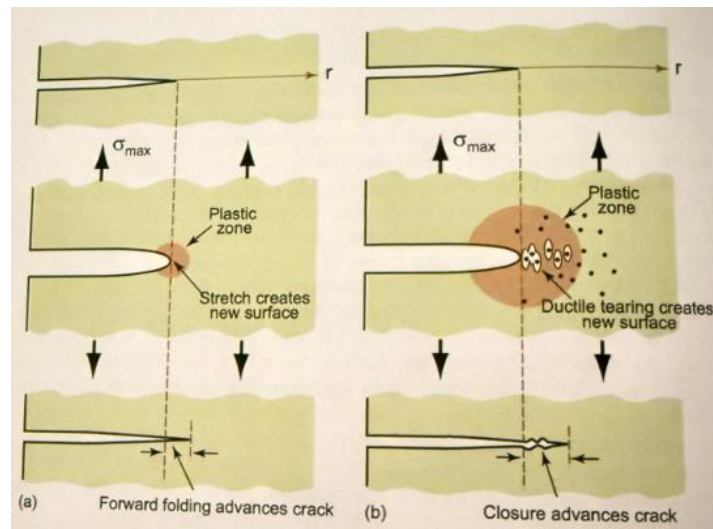


Figure 12 Plastic Zone Behaviour and Crack Advance in Ductile Materials (a) High-cycle: Small plastic zone, forward folding advances crack. (b) Low-cycle: Large plastic zone, voids nucleate and coalesce for ductile tearing [5].

Figure 12 shows In **high-cycle fatigue** stresses are lower and the plastic zone at the crack tip is small. The crack opens and advances slowly through small-scale plastic stretching and folding

In **low-cycle fatigue** the plastic zone is much larger. This big plastic area causes tiny voids to form, grow, and join together, just like in a normal ductile tear. The crack advances faster through this void coalescence process. [2]

This is why the final overload fracture in the wheel hub shows a rough, fibrous surface: ductile tearing with micro voids after the slow fatigue growth phase [6].

2.6 Testing Methodologies in Failure Analysis

The following tables 1, 2 and 3 summarise the analytical and inspection techniques relevant to characterising the wheel-hub material, identifying the fracture mode, and assessing the presence of surface or subsurface damage. Together, they outline the range of methods typically applied in a comprehensive fatigue-failure investigation.

2.6.1 Mechanical Testing

Table 1 Mechanical Testing Methods in Failure Analysis [7] [8]

Mechanical Testing	Purpose	What it Measures	Relevance to Component Failure
Test Method			
Hardness Testing	Evaluates surface resistance to indentation using methods such as Rockwell, Vickers, or Brinell.	Indirect indicators of strength, heat-treatment condition, and material uniformity.	Helps identify thermal degradation, or softening caused by braking-induced heat. Variations in hardness can suggest whether material weakening contributed to crack initiation or growth.
Tensile Testing	Determines bulk mechanical properties under controlled loading.	Yield strength, ultimate tensile strength, ductility, toughness, and elastic modulus.	Confirms whether the wheel hub material still meets design properties. Reduced strength or toughness can explain accelerated fatigue crack propagation or premature fracture.

2.6.2 Chemical Testing

Table 2 Chemical Testing Methods in Failure Analysis [9]

Chemical Testing	Purpose	What it Measures	Relevance to Component Failure
Test Method			
Optical Emission Spectroscopy (OES)	Determines elemental composition using light emitted from an excited sample.	Major alloying elements and some trace elements.	Confirms alloy family when certification is unavailable, supporting interpretation of expected fatigue and fracture behaviour.

2.6.3 Microscopic Testing

Table 3 Microscopic Testing Methods in Failure Analysis [10] [11] [12] [7]

Microscopic Testing	Purpose	What it Measures	Relevance to Component Failure
Test Method			
Energy-Dispersive X-ray Spectroscopy (EDS)	Micro-scale compositional analysis during SEM imaging.	Local chemistry of inclusions, segregated phases, or second-phase particles.	Helps identify microstructural features that may act as crack initiation sites.
Eddy Current Testing (ECT)	Electromagnetic method for detecting surface and near-surface defects.	Surface-breaking cracks, corrosion, conductivity variations, and heat-affected zones.	Useful for identifying small fatigue cracks around bolt holes, fillet radii, and bearing bores without disassembly.
Ultrasonic Testing (UT)	Uses high-frequency sound waves to detect internal flaws	Subsurface cracks, voids, delaminations, and thickness variations.	Helps detect deeper fatigue cracks or internal defects within the hub wall that are not visible externally.
Fluorescent Penetrant Inspection (FPI)	Dye-based method for revealing surface-breaking defects under UV light.	Fine surface cracks, porosity, and discontinuities.	Ideal for detecting early fatigue cracks at the hub's fillet radii, bolt holes, and bearing seats, especially where cracks initiate at the surface.

3 Case Study Analysis

3.1 Failure Mechanism Identification

The failure of the Boeing 737 NG main landing gear (MLG) wheel hub is assessed to have occurred as a result of high-cycle fatigue leading to final overload fracture. The component examined was the inboard half of the wheel hub, seen in Figure 13, a highly stressed, safety-critical structural element responsible for transmitting landing, braking, and taxi loads from the wheel assembly into the landing gear structure.

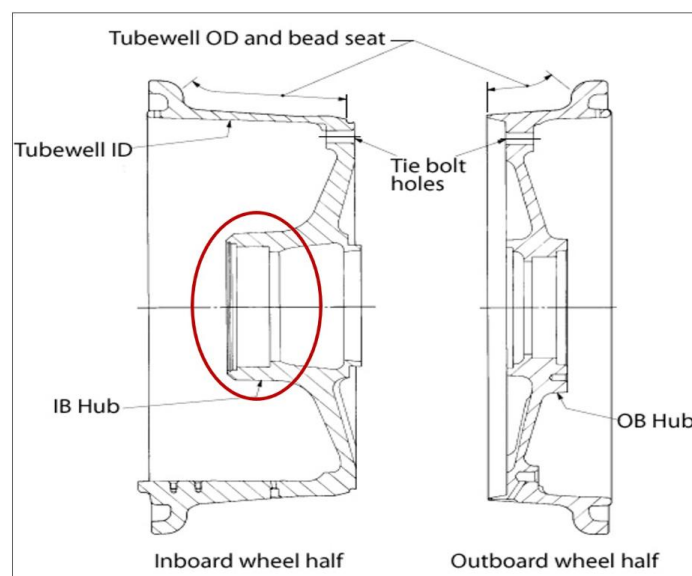


Figure 13 Schematic Diagram of Wheel Hub with the Failure Location Circled [13]

Although the exact alloy composition and heat-treatment condition of the failed hub were not publicly disclosed due to proprietary constraints, aerospace wheel hubs of this class are typically manufactured from high-strength, precipitation-hardened aluminium alloys, most commonly AA7075-T6 or, in some applications, AA2024-T351 [14]. These alloys are selected for their exceptional strength-to-weight ratio, fracture toughness, and fatigue resistance, all of which are essential for cyclic load-bearing components in aircraft landing systems.



Figure 14 Exposed Wheel Bearing Fracture on Main Landing Gear Assembly [13]

3.2 Fatigue Initiation

Fatigue is defined as a progressive and localised form of material damage that occurs when a component is subjected to repeated or fluctuating stresses, typically well below the material's ultimate tensile strength. In aircraft wheel hubs, fatigue represents a life-limiting failure mode due to the extremely high number of load cycles accumulated over service life, including landings, braking events, and ground manoeuvring [15].

Fractographic examination of the failed hub, Seen in Figure 15, revealed features characteristic of fatigue failure, included:

- Crack initiation at a localised geometric discontinuity
- Stable crack growth over an extended period
- Final catastrophic overload once critical crack size was reached

Distinct beach marks were observed on the fracture surface in Figure 15, indicating intermittent crack growth corresponding to variations in operational loading. These macroscopic fatigue markings provide strong evidence that the crack propagated incrementally over many service cycles before ultimate failure.

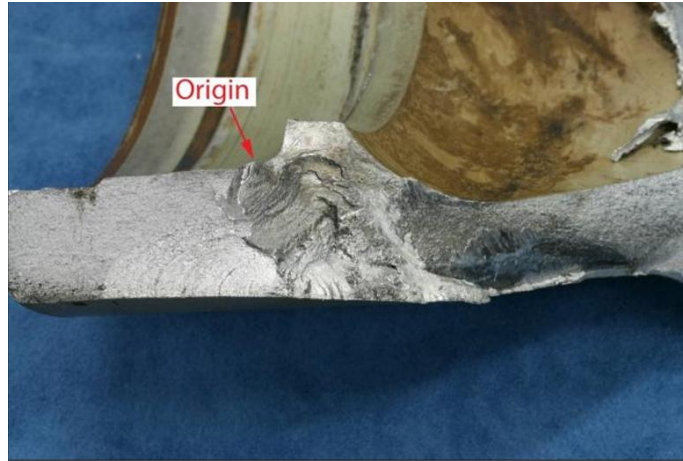


Figure 15 Fatigue Fracture Surface Showing Beach Marks and Crack Origin [13]

The dull grey, fibrous fracture surface corresponds to ductile overstress failure. Its morphology indicates a sudden overload event, with no evidence of the smooth, progressive crack growth typically associated with fatigue.

3.3 Crack Initiation

Crack initiation is assessed to have occurred at the bearing bore corner radius, a region known to experience elevated local stresses due to both geometry and loading conditions [7]. This area, seen in Figure 16, represents a transition between the cylindrical bearing seat and the hub wall, where relatively small fillet radii can produce significant stress concentration effects.



Figure 16 Crack Initiation at Bearing Bore Corner Radius

3.3.1 Crack Orientations

Figure 17 shows the fatigue cracks grew in two main directions:

- **Axial cracks** - running along the length of the hub (parallel to the axle).
- **Circumferential cracks** - running around the hub (like rings around the bore).

These multiple directions show the complex stresses acting on the bearing bore area, radial pressure pushing outward and torsional/shear forces twisting the hub. The cracks eventually linked up, leading to the final fracture and hub separation.



Figure 17 Fractured Hub Section [13]

3.3.2 Further Crack Detection Using Fluorescent Penetrant Inspection (FPI)

To check for other cracks, the remaining parts of the inboard hub were inspected using fluorescent penetrant inspection (FPI), seen in Figure 18 and Ultrasonic testing (UT). This technique revealed multiple radial and circumferential cracks in the bearing bore radius area [13]

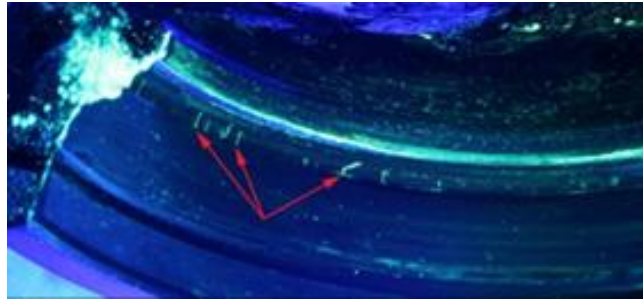


Figure 18 Radial Cracks Found by FPI [13]

3.3.3 Stress Concentrations Effects

Features such as sharp fillets or bore shoulders create elevated local stresses, reflected in a higher stress-concentration factor, seen in Figure 19. Under landing loads that can approach several times the aircraft's static weight, these localised stresses may repeatedly exceed the material's fatigue endurance limit, despite remaining below yield strength.

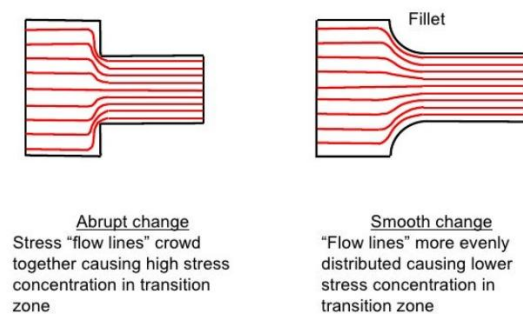


Figure 19 Stress Concentrations [16]

The bearing bore region is additionally subjected to:

- Radial compressive stresses from bearing press-fit
- Compressive stresses from wheel inflation pressure
- Bending and torsional stresses induced during aircraft ground operations

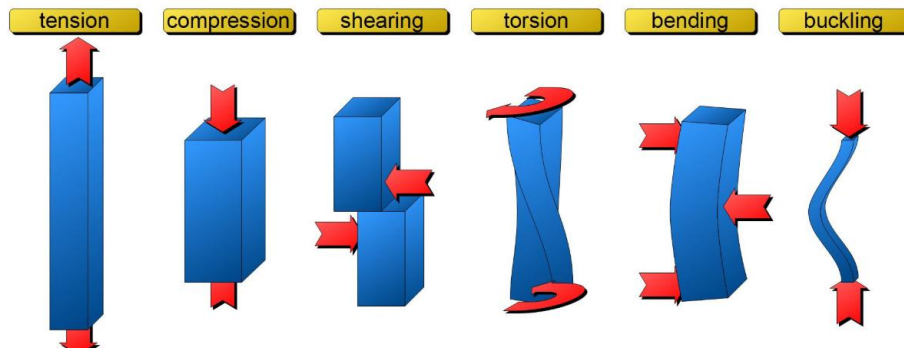


Figure 20 Types of Material Stresses & Forces [17]

The superposition of these stresses, seen in Figure 20, produce a complex multiaxial stress state that is particularly damaging under cyclic conditions, altering the direction and rate of crack growth, making the propagation behaviour more complex than what would occur under a single dominant load.

3.3.4 Microstructural Inclusions

High-strength aluminium alloys such as AA7075/2024 (Table 4), are particularly sensitive to microstructural heterogeneities during cyclic loading [18]. These alloys contain hard, brittle intermetallic particles enriched with elements such as iron, copper, and magnesium [14]. Under repeated stress, these particles can fracture, separate from the surrounding matrix, or act as sites for early micro-void formation. Once small cracks form at these locations, they can link together under continued loading and develop into a dominant fatigue crack within the hub material [19].

Table 4 Material Composition AA7075 and AA2024 [14]

ELEMENT	Composition (%)	
	2024 Alloy	7075 Alloy
Si	0.5	0.4
Fe	0.5	0.5
Cu	3.8-4.9	1.2-2.0
Mn	3.0-0.9	0.3
Mg	1.2-1.8	2.1-2.9
Cr	0.1	0.18-0.28
Ni	–	–
Zn	0.25	5.1-6.1
Ti	0.15	0.2
Others:Each	0.005	0.05
Others:Total	0.15	0.15
Aluminum	Remainder	Remainder

Environmental exposure can further accelerate crack initiation. Moisture, de-icing chemicals, and thermal cycling can promote localised corrosion or coating breakdown, producing small pits that act as additional stress concentrators. Even minor surface damage in highly stressed regions can significantly reduce the number of cycles required for a crack to form [20].

Surface condition also plays a critical role. Shot peening introduces a layer of beneficial compressive residual stress that suppresses crack initiation, but in this case the bearing-bore radius was not treated. As a result, this transition region lacked the protective compressive layer and remained vulnerable to fatigue under service loading. The presence of multiple radial and circumferential cracks around the bore is consistent with a highly stressed, un-peened region subjected to complex cyclic loading [13].

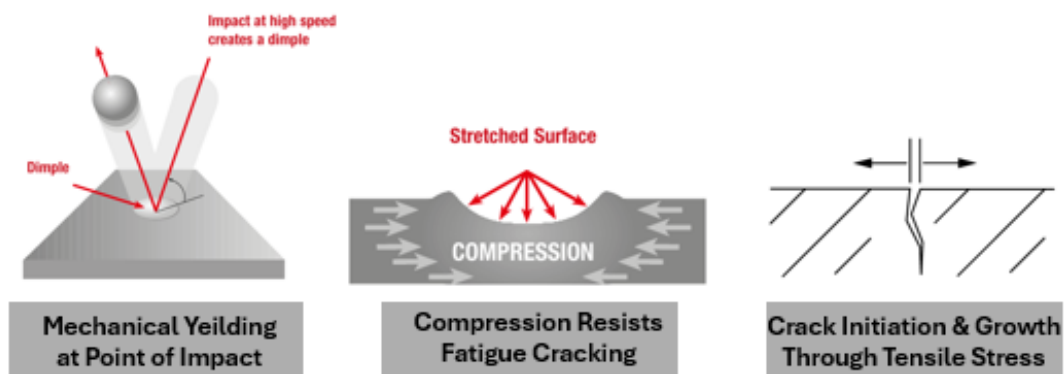


Figure 21 Shot Peening Process [21]

Both environmental exposure and manufacturing-related factors, such as inclusions, machining marks, and incomplete shot-peening, can significantly reduce fatigue resistance by creating local stress concentrations that promote early crack initiation [21].



Figure 22 Radial/Axial Cracks Adjacent to the Shot-Peened Area (High Magnification) [13]

High-magnification examination in Figure 22, confirmed these cracks were mostly radial and positioned right next to the shot-peened region. This shows the area outside the peened zone was highly stressed and unprotected, allowing extra cracks to start.

3.3.5 Ideal Grain Structure

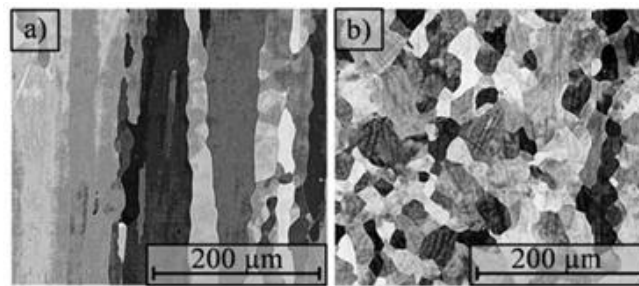


Figure 23 Columnar Grain Structure (A), and Equiaxed Grain Structure (B) [22]

Fatigue crack initiation is strongly influenced by intermetallic particle size, particle clustering, and grain morphology, with large particles or coarse grains acting as stress concentrators, particularly in geometrically stressed regions. Under cyclic loading, cracks preferentially initiate and propagate along microstructural paths of least resistance, and initiation life is further reduced in the absence of residual stresses. Fatigue-critical aerospace components such as aircraft wheel hubs, an optimal material condition combines a fine, equiaxed grain structure, seen in Figure 23, with controlled alloy chemistry, minimising brittle iron-rich intermetallic while maintaining a balanced precipitation-hardened microstructure [22].

3.4 Fracture Mechanics

Fracture mechanics provides a framework for interpreting the observed crack growth and final failure of the wheel hub. The presence of well-defined fatigue features such as beach marks and multiple crack fronts indicates stable crack propagation under cyclic loading, consistent with Paris-law behaviour where crack growth rate is governed by the stress intensity range ΔK [6].

As cracks initiated at the bearing-bore radius and grew circumferentially and axially, the effective crack length increased, leading to a corresponding increase in stress intensity factor K , as described by [2]:

$$K = Y\sigma\sqrt{\pi a}. \quad 3-1$$

Throughout most of the service life, $K_{max} < K_{IC}$ allowing progressive fatigue crack growth rather than immediate fracture.

Final failure occurred once the crack reached a critical size such that the applied stress intensity exceeded the plane-strain fracture toughness K_{IC} of AA7075. At this point, stable fatigue propagation transitioned to rapid overload fracture, producing the dull, fibrous fracture surface associated with ductile microvoid coalescence.

- K is the stress intensity factor ($\text{MPa}\sqrt{\text{m}}$), which quantifies how strongly a crack is being driven to grow.
- σ is the applied tensile or cyclic stress acting on the component.
- a is the crack length (or half-crack length, depending on geometry).
- Y is a dimensionless geometry factor that accounts for crack shape, location, and component geometry (e.g. edge crack, internal crack, bore radius).

4 Discussion

The Boeing 737 wheel hub failure demonstrates the interaction between material behaviour, geometric design, service loading, and inspection strategy in fatigue-critical aerospace components. Although high-strength aluminium alloys such as AA7075 provide excellent strength-to-weight performance, this case confirms their vulnerability to fatigue when local stress concentrations and unfavourable surface conditions are present.

Fractographic evidence supports a high-cycle fatigue failure mechanism. Beach marks, multiple crack fronts, and a distinct final overload region indicate long-term stable crack growth followed by rapid fracture. Crack initiation at the bearing-bore shoulder radius is consistent with known stress concentration effects and confirms the relevance of fracture mechanics concepts applied in this report, including Paris-law controlled propagation.

Manufacturing and design factors played a significant role. Incomplete shot-peening coverage at the bearing bore radius removed a key fatigue-mitigation feature from the most highly stressed region. Combined with press-fit bearing stresses and multiaxial service loading, this significantly reduced crack initiation life and allowed multiple cracks to form circumferentially.

The case also highlights limitations in inspection strategy. Traditional surface-based inspections were not well suited to detecting subsurface fatigue cracks initiating beneath bearing seats. The delayed implementation of ultrasonic inspection allowed cracks to grow undetected to critical size, reinforcing the need to align inspection techniques with anticipated failure modes.

Overall, the failure resulted from the cumulative interaction of material sensitivity, geometric stress concentration, loading environment, and inspection limitations, rather than a single isolated cause.

5 Conclusion

This report concludes that the Boeing 737 main landing gear wheel hub failed due to high-cycle fatigue cracking initiated at the bearing-bore shoulder radius, followed by stable crack growth and final ductile overload fracture. Macroscopic and microscopic fracture features provide clear evidence of this sequence.

The bearing-bore radius was identified as a critical location due to stress concentration, press-fit bearing loads, and complex multiaxial stresses during landing and ground operations. While AA7075 offers high strength, its reduced fracture toughness and sensitivity to surface condition increased susceptibility to fatigue initiation, particularly in the absence of compressive residual stresses from shot peening.

Fracture mechanics analysis explains the observed transition from stable crack growth to sudden failure as increasing crack length elevated the stress intensity factor beyond the material's fracture toughness. The case reinforces the importance of integrating materials science, structural mechanics, and inspection planning in the management of safety-critical aerospace components.

6 Recommendations

Fatigue-critical regions such as bearing-bore shoulder radii should receive full shot-peening coverage to introduce beneficial compressive residual stresses. Manufacturing processes should promote fine, equiaxed grain structures and high alloy cleanliness to minimise brittle intermetallic inclusions that act as crack initiation sites.

Material selection should continue to balance strength and fracture toughness, with consideration given to alternative tempers or local material optimisation in highly stressed regions. Improved surface finishing and tighter control of machining quality at transition radii are also recommended.

Maintenance strategies should prioritise volumetric non-destructive testing methods, such as ultrasonic inspection, where subsurface crack initiation is expected. Strict adherence to bearing installation and torque procedures is essential to prevent abnormal stress states. Together, these measures support a damage-tolerant approach that enhances safety and extends component service life.

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