Aircraft Landing Gear Fracture

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The right landing gear on a twin-turboprop transport aircraft collapsed during landing. Preliminary examination indicated that the failure occurred at a steel-to-aluminum (7014) pinned drag strut connection due to fracture of the lower set of drag strut attachment lugs at the lower end of the oleo cylinder housing. Two lug fractures that were determined to be the primary fractures were analyzed. Results of various examinations indicated that stress-corrosion cracking associated with the origins of the principal fractures in the connection was the cause of failure. It was recommended that the design be modified to avoid dissimilar metal combinations of high corrosion potential.

Key Words
Aluminum-base alloys
Landing gear
Stress-corrosion cracking
Transition joints
Steels
Airplanes

Alloys
Aluminum-base alloy—7014

Background
A twin-turboprop transport aircraft sustained considerable damage when one of its main landing gear assemblies collapsed during landing.

Applications
The aircraft had an 18,000 kg (40,000 lb) gross landing weight and tricycle landing gear. The main landing gear was equipped with two wheels on each side in the general configuration shown in Fig. 1. This assembly was the principal support for the aircraft and had many components, including airfoil shock struts to absorb landing impact and taxing loads, alignment and support units, retraction mechanism and safety devices, auxiliary gear protective devices, wheels, tires, tubes, and braking systems. Components of specific interest are shown in Fig. 2.

Shock (or oleo) struts are self-contained hydraulic units that use compressed air combined with hydraulic fluid to absorb and dissipate their imposed loads. Each shock strut comprises two telescoping cylinders with externally closed ends. The assembly is equipped with an axle at the lower end for mounting the wheels and with torque arms to maintain correct wheel alignment.

The various pivoted linkages (see Fig. 2) have several important functions. They serve not only to support the aircraft during landing and ground movement and to maintain proper alignment and spacing of the wheels with respect to the fuselage, but also to provide a mechanism for retracting the wheels after takeoff and extending them before landing. These are highly stressed structural members, and cracks or fractures in any of them or loss of integrity of their connections or attachment points can lead to serious consequences.

Circumstances leading to failure
The aircraft had been in service for 28 years since its manufacture, and the landing gear was of original design, if not the original equipment. Upon touchdown during a routine landing in a crosswind, the starboard (right) set of wheels of the main landing gear first contacted the runway. As the weight of
the aircraft began to settle on the gear, a sharp thud was heard coming from the direction of the right undercarriage. It was immediately evident that the right landing gear was not supporting the aircraft, because that side of the aircraft dropped to the ground, with the aircraft now supported only by the left landing gear and nosewheel. This caused the right wing tip, the propeller blades of the right engine, and the lower portion of the rear fuselage to scrape along the runway, resulting in substantial damage.

Subsequent jacking of the fuselage and wing permitted removal of the right landing gear assembly. The lower set of drag-strut attachment lugs at the lower end of the oleo cylinder housing was found to have fractured and separated. This caused the right undercarriage (entire strut assembly and wheels) to pivot backward about the upper strut gear retraction hinge points (as if in retraction mode), resulting in loss of right-side support for the aircraft.

Design documents and stress/load calculations for the affected components showed adequate safety margins well within regulation limits. This was confirmed by a nearly 30-year period of satisfactory service and component performance. The oleo cylinder forging was identified as an age-hardenable aluminum alloy (type 7014) of British origin. British Specification AP970, in use at the time the aircraft was manufactured, indicated weight advantages for high-strength zinc-bearing aluminum alloys used in aircraft applications, but also pointed out their susceptibility to stress cracking and stress corrosion and their limited ductility in the fully heat-treated condition.

Figure 3 shows the affected strut cylinder and fractured lower drag-strut attachment lugs (smaller arrows). In Fig. 3, the triangular drag-strut attachment yoke is shown rotated back about the still intact upper attachment lug pivot. The 25.4 mm (1 in.) diam unsleeved steel attachment pin for the bottom set of fractured lugs is still in position within the yoke (large arrow). Figure 4 shows a more detailed view of the two lug fractures (four fracture faces), which became the principal focus of the study, as these were determined to be the primary fractures.

One other location on the main strut assembly contained a fractured component, but all evidence indicated that this was a secondary occurrence caused by failure of the lower pair of connecting lugs and subsequent pivoting of the drag-strut connecting yoke about the upper pin. The lug attachment protrusions (see Fig. 4) below the fractures showed no evidence of plastic deformation. The inner edges (i.e., toward the attachment pin recess) of the fractures of the lower portions of the two lugs showed signs of scuffing that probably occurred during the incident or during subsequent removal of the landing gear components. Lug recesses where the steel pin had been were dirty and discolored.

Visual
Examination
of General
Physical
Features

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Testing
Procedure
and Results

Surface
examination

Visual. There was virtually no observable plastic deformation associated with the primary fractures, as all had a brittle appearance. The fractured surfaces were dull gray in color and granular in texture. One of these surfaces (upper left segment) also exhibited a fan-shaped area of lightly tinted yellow-brown discoloration that was not present on other fractures. There were apparent differences among the four faces in fracture origin and propagation direction, which prompted examination at higher
magnifications. Such examinations required cleaning of the fractured surfaces, but this was deferred until chemical analyses of the surfaces were completed so that corrosion residues, if present, would not be lost.

**Macrofractography.** After cleaning, the fractures were examined optically at higher magnifications (up to about $20\times$). These examinations showed that the fracture in the upper left portion of the lug originated at the surface of the steel pin. There were indications that the fracture in the upper right lug also may have originated at the surface of the steel pin. Figures 5(a) to (d) are oriented in the same position that the fractures occurred on the strut cylinder, with the hole for the steel pin located between the upper and lower fractures.

Even in these relatively low-magnification examinations, it was evident that the fracture at the left upper lug appeared different from the other three fractures in several respects: (1) the fracture had a flatter profile; (2) it apparently had multiple origins along the bolt (i.e., attachment pin) hole; (3) it apparently progressed in at least two, and perhaps as many as five or more, stages; and (4) in the as-received condition, a fan-shaped discolored area extended over half of the fractured area. Because of these features, the upper left fractured segment was thought to be the initiating point for the failure.

Further examination in the region of the upper left fracture revealed a number of cracks at the surface of the hole for the attachment pin. These cracks generally ran in a direction parallel to the fractured surface, as in Fig. 6, which shows the surface perpendicular to the axis of the hole and hole surface, with the fractured edge visible at the top of (a) and (b). Because it was conceivable that the sudden wrenching of the 25 mm (1 in.) steel pin during fracturing of the lugs could have produced these cracks within the hole, considerable attention was given to
these cracks to establish whether they existed before the incident or were produced as a result of it.

A number of indications pointed to their preexistence. One is that these cracks, as observed in the as-received components, were packed with debris and other matter of the same color, appearance, and texture as that found elsewhere on the steel pin and the inner surfaces of its attachment hole. None of these cracks had the shiny metallic luster typical of fresh fractures. Examinations of the hole surfaces adjacent to the other three fractures revealed the presence of similar cracking at the hole adjacent to the fracture at the lower left lug segment (i.e., the same hole on the same side), but none was observed at the fractures on the right side (either the upper or lower regions).

**Scanning Electron Microscopy/Fractography.** Examination of the fracture surfaces of the attachment lugs by scanning electron microscopy (SEM) showed that, despite the macroappearance of brittleness, most of the fracture surface had failed in a ductile manner with fairly large regions of microvoid coalescence associated with numerous nonmetallic inclusions (apparently characteristic of this alloy). However, in regions near the hole for the attachment pin, particularly in the upper left fracture, SEM examinations revealed surfaces typical of those experiencing stress-corrosion cracking (SCC). In Fig. 7, note the evidence of grain-boundary separation. Such surfaces showed no evidence of ductility. Similar SEM examinations were conducted on the fracture of the lug on the right side. These showed little, if any, evidence of secondary (intergranular) fracturing.

**Metallography**

**Microstructural Analysis.** Metallographic examinations of material from the fractured lug (but located closer to the body of the strut cylinder) in both etched and unetched conditions revealed a microstructure typical of a 7xxx aluminum alloy.
forging. Cross sections were also made of fractures where examinations showed cracks along the attachment pin hole adjacent to the fractured surfaces (i.e., at the left lug).

**Crack Origins/Paths.** Examinations of polished but unetched surfaces of cross sections normal to the hole axis and the secondary crack planes revealed a condition of secondary cracking, initiating at corrosion pits in the aluminum, running along the surface of the hole, and extending well into the material. Figure 8 shows cracks found in the upper left lug. As shown in Fig. 9, light etching and higher magnification revealed that the cracks were intergranular.

**Chemical analysis/identification**

Material. Results of chemical analysis of the landing gear strut cylinder are shown in Table 1. Comparisons of this composition within the range of known commercial alloys of this general type showed it to correspond closely to type 7014.

**Corrosion Deposits.** Comparative energy-dispersive spectroscopy (EDS) analyses of the discolored fan-shaped region of the upper left fracture with regions outside it (but still within the fractured surface) revealed a higher iron content within the discolored region. This finding suggested that the discoloration was iron oxide, possibly originating from the adjacent steel pin and adding further support that this region had cracked previously, allowing iron-containing moisture to seep by capillary action along the crack surface over time. Other than the consistently higher iron content of this fan-shaped region, no other compositional anomalies were observed. EDS analysis failed to provide conclusive identification of the debris packed into the cracks along the pin attachment holes. The material was tentatively identified as an organic residue, perhaps from a deteriorated coating that had been applied to the 25 mm (1 in.) diam pin during assembly.

**Associated Environments.** Aircraft landing gear are subjected to a wide range of temperatures, wet and dry environmental conditions, and climates ranging from arid to marine. Moisture that contains chlorides is commonly encountered in flights over oceans and in coastal areas, and temperature fluctuations are frequent.

**Table 1 Results of chemical analysis**

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition, %</th>
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<tbody>
<tr>
<td>Aluminum</td>
<td>bal</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.15 (max)</td>
</tr>
<tr>
<td>Iron</td>
<td>0.28 (max)</td>
</tr>
<tr>
<td>Copper</td>
<td>0.47</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.47</td>
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<tr>
<td>Magnesium</td>
<td>2.90</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.005</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.03 (max)</td>
</tr>
<tr>
<td>Zinc</td>
<td>5.31</td>
</tr>
<tr>
<td>Titanium</td>
<td>0.04</td>
</tr>
<tr>
<td>Vanadium</td>
<td>0.01</td>
</tr>
<tr>
<td>Zirconium</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>Total impurities</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>0.05 (max)</td>
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</tbody>
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(a) From Key To Aluminum Alloys, Designations, Compositions, Trade Names of Aluminum Materials, 1st ed., W. Hufnagel, Ed., Aluminum-Zentral, July 1982. (b) Plus zirconium

Although in macroexaminations secondary cracking appeared to be confined to the hole surfaces at the left attachment lug, a cross section of the lower right fracture also showed a condition of branched cracking stemming from corrosion pits. The cracking observed at the right side (Fig. 10), however, was not as advanced as the cracking in the left lug; the cracks were shallower and not as numerous (note the differences in magnification in Fig. 8 to 10).

**Mechanical properties**

**Hardness** determinations showed this alloy to have a Brinell hardness of 174 HB (using a 3000 g load and a 10 mm hardened steel ball indenter). Hardness data on 7014 aluminum alloy in various tempers were not readily available; however, this hardness is comparable to the hardness of 7075 aluminum in the T6 (artificially aged) condition (7075 alloy composition: 5.6% Zn, 2.5% Mg, 1.6% Cu, 0.23% Cr, with the balance essentially aluminum).

**Discussion**

Results of electrical conductivity determinations showed the strut alloy to have a conductivity of 31.3% IACS (International Annealed Copper Standard). Again, conductivity data for the 7014 alloy in various tempers were unavailable; however, this conductivity compares closely with a T651 condition for alloy 7075. It is of interest to note that this temper in alloy 7075 is not considered an optimal condition for resisting SCC.

A number of indications pointed to the preexistence of cracks in the drag-strut attachment lugs. Possibly the most compelling evidence was the intergranular nature of the cracks. They initiated at corrosion pits at the steel pin/aluminum hole interface and probably were accelerated by hydrogen generated at the electrolytic cell created by the steel/aluminum dissimilar metal couple in the presence of moisture.
Stress corrosion at such a location in 7xxx series aluminum alloys is not uncommon. Stress necessary for its occurrence could have come from a number of sources, such as residual stress introduced during manufacture of the component (hole drilling and reaming), the fit of the steel pin to the hole, cyclic differential expansion and contraction of the dissimilar metal couple over the wide range of aircraft operating temperatures, and repetitive application of mechanical force on the surface of the hole in the aluminum lug by the attachment pin during landing and ground maneuvering of the aircraft and during gear retraction and extension.

Although this particular aluminum alloy is not commonly encountered in the U.S., its microstructure and fracture response seem consistent with its chemical composition. There is some question as to its temper and suitability for this service in this condition, because the alloy is an age-hardenable grade and its resistance to stress corrosion can be influenced by temper or age-hardening heat treatment.

**Conclusion and Recommendations**

**Most probable cause**

It appears that, over time, the protective insulating coatings on the steel pin and in the holes in the aluminum (presuming coatings were originally applied) deteriorated, permitting moisture to seep along the unprotected surfaces of the aluminum and steel pin and produce localized corrosion pits in the aluminum at the steel/aluminum interface. Possibly, localized fretting at this location may have contributed to coating perforations that assisted in initiating the corrosion pits. These apparently became favored sites for stress corrosion, particularly where tensile stress was high. Once stress-corrosion cracks developed along the hole surface and propagated into the aluminum lugs (in a direction radially outward from the steel pin), these multiple crack fronts constituted buried flaws of high stress intensity within a material of questionable fracture toughness.

With this condition at this critical location, a single crack—or several merging together into a dominant front—would eventually approach critical size. At that time, its propagation would become unstable, causing it to easily and rapidly progress a relatively large distance into the aluminum lug, or until its propagating energy dissipated. The findings of this study indicate that this occurred in the upper left lug, probably with the first unstable growth causing the crack to reach the perimeter of the fan-shaped (discolored) region. The crack could have remained arrested at that point for some time before additional stress caused it to propagate further, possibly augmented by combinations of stress corrosion and fatigue.

When this occurred, complete fracture of the lug would have been imminent. The study showed that stress-corrosion cracks had also developed in the right lug, although at an apparently less advanced stage. Nevertheless, such cracks would constitute sharp-edged flaws that readily propagate under moderate impact loading. Therefore, with failure of the left attachment lug, fracture of the right lug would also be assured—if not from brittle fracture, then from impacting overload.

**Remedial action**

It is common, in the aftermath of failures, to speculate on detectability of preexisting cracks that ultimately result in catastrophic collapse of a structural component. It is likely that a crack as large as the fan-shaped region in the upper left lug would be detectable by present nondestructive evaluation techniques. However, to detect such a crack, these techniques would have had to have been applied at the right time (after it formed and before the failure incident) and in the right location of the landing gear strut. Furthermore, to obtain an unambiguous indication, it probably would have been necessary to disassemble the yoke from the oleo cylinder by removing the attachment pins. Perhaps more significantly, it would have been considerably more difficult, if not impossible under the circumstances (and after withdrawing the steel pins), to detect the much shallower SCC within the holes in the aluminum lug.

It was recommended that, notwithstanding the practical difficulties of detecting the presence of incipient cracks within attachment pin locations, procedures be developed that would ensure the integrity of critical, nonredundant components and that they be implemented in aircraft having such components. It was emphasized that special attention should be given to components in which dissimilar couples (e.g., steel to aluminum) exist or could exist, exposing the steel to hydrogen embrittlement and/or the aluminum to SCC. It was further suggested that alternatives to semipermanently pinned joints, particularly those involving dissimilar materials, be devised and implemented on existing aircraft.