

ACCIDENT

Aircraft Type and Registration:	Boeing 737-476(SF), EI-STD	
No & Type of Engines:	2 CFMI CFM56-3C1 turbofan engines	
Year of Manufacture:	1990	
Date & Time (UTC):	29 April 2014 at 0128 hrs	
Location:	East Midlands Airport	
Type of Flight:	Commercial Air Transport (Cargo)	
Persons on Board:	Crew - 2	Passengers - None
Injuries:	Crew - None	Passengers - N/A
Nature of Damage:	Left main landing gear, left wing and engine	
Commander's Licence:	Airline Transport Pilot's Licence	
Commander's Age:	38 years	
Commander's Flying Experience:	4,279 hours (of which 377 were on type) Last 90 days - 114 hours Last 28 days - 10 hours	
Information Source:	AAIB Field Investigation	

Synopsis

During the landing rollout at East Midlands Airport, as the aircraft's speed reduced through 60 kt, the co-pilot handed control to the commander who then made a brake pedal application to disengage the autobrake system. The aircraft shuddered and rolled slightly left-wing-low as the lower part of the left main landing gear (MLG) detached. The MLG inner cylinder had fractured through its chrome plated section, approximately 75 mm above the axle, allowing the left mainwheels and brakes to detach.

The cause of the fracture was stress corrosion cracking and fatigue propagation within the high strength steel substrate, leading to ductile overload failure. This was as a result of a small but significant area of localised heat damage to the chrome plating, leading to the exposure of the substrate to a corrosive environment. The exact source of the heat could not be determined.

History of the flight

The aircraft was scheduled to operate three commercial air transport (cargo) sectors: from Athens to Bergamo, then to Paris Charles de Gaulle, and finally East Midlands.

The aircraft's flap load relief system was inoperative, which meant that the maximum flap position to be used in flight was 30, rather than 40°. This defect had been deferred in the aircraft's technical log and it had no effect on the landing of the aircraft. Otherwise, the aircraft was fully serviceable.

The co-pilot completed the pre-flight external inspection of the aircraft in good light, and found nothing amiss. The departure from Athens was uneventful, but a combination of factors affecting Bergamo (including poor weather, absence of precision approach aids, and work in progress affecting the available landing distance) led the crew to decide to route directly to Paris, where a normal landing was carried out.

The aircraft departed Paris for East Midlands at 0040 hrs, loaded with 10 tonnes of freight, 8 tonnes of fuel (the minimum required was 5.6 tonnes), and with the co-pilot as Pilot Flying.

Once established in the cruise, the flight crew obtained the latest ATIS¹ information from East Midlands, which stated that Runway 27 was in use, although there was a slight tailwind, and Low Visibility Procedures (LVPs) were in force. They planned to exchange control at about FL100 in the descent, for the commander to carry out a Category III autoland. However, as they neared their destination, the weather improved, LVPs were cancelled, and the flight crew re-briefed for an autopilot approach, followed by a manual landing, to be carried out by the co-pilot. The landing was to be with Flap 30, Autobrake 2, and idle reverse thrust.

The final ATIS transmission which the flight crew noted before landing stated that the wind was 130/05 kt, visibility was 3,000 metres in mist, and the cloud was broken at 600 ft aal.

The commander of EI-STD established radio contact with the tower controller, and the aircraft was cleared to land; the surface wind was transmitted as 090/05 kt. The touchdown was unremarkable, and the autobrake functioned normally, while the co-pilot applied idle reverse thrust on the engines.

As the aircraft's speed reduced through approximately 60 kt, the co-pilot handed control to the commander, who then made a brake pedal application to disengage the autobrake system. However, the system remained engaged, so he made a second, more positive, brake application. The aircraft "shuddered" and rolled slightly left-wing-low as the lower part of the left main landing gear detached. The commander used the steering tiller to try to keep the aircraft tracking straight along the runway centreline, but it came to a halt slightly off the centreline, resting on its right main landing gear, the remains of the left main landing gear leg, and the left engine lower cowl (Figure 1). The co-pilot saw some smoke drift past the aircraft as it came to a halt.

The co-pilot made a transmission to the tower controller, reporting that the aircraft was in difficulties, after which the co-pilot of another aircraft (which was taxiing from its parking position along the parallel taxiway) made a transmission referring to smoke from the 737's landing gear. The commander of EI-STD had reached the conclusion that one of the main landing gear legs had failed, but as a result of the other pilot's transmission, he was also concerned that the aircraft might be on fire.

The commander immediately moved both engine start levers to the cut-off positions, shutting down the engines. Three RFFS vehicles had by now arrived at the adjacent taxiway

Footnote

¹ Automatic Terminal Information Service.

intersection, and their presence there prompted the commander to consider that the aircraft was not on fire (he believed that if it were, the vehicles would have adopted positions closer by and begun to apply fire-fighting media).



Figure 1

View of aircraft and detached section of lower left MLG

The RFFS vehicles then moved closer to the aircraft and fire-fighters placed a ladder against door L1, which the co-pilot had opened. Having spoken to fire-fighters while standing in the entrance vestibule, the commander returned to the flight deck and switched off the battery. The flight crew were assisted from the aircraft and fire-fighters applied foam around the landing gear and engine to make the area safe. The commander had taken the Notoc² with him from the aircraft, and informed fire-fighters of the dangerous goods on board the aircraft.

Communications

A variety of factors caused some communications, between ATC and other agencies, not to flow as smoothly as might have otherwise been the case. These difficulties centred mostly on lack of clarity in communications, non-standard terminology (or different terminology used by different agencies), confusion in lines of communication between agencies, and lack of appropriate prioritisation of communications tasks. The airport, and other agencies, reviewed these matters, and the action taken is summarised under 'Safety actions'.

Recorded data

The aircraft was fitted with a 30-minute Cockpit Voice Recorder (CVR) and a Flight Data Recorder (FDR) that captured more than 40 hours of flying.

Footnote

² Notice to Captain: the document detailing dangerous goods in the freight.

Due to limitations of the FDR parameter requirements and faults associated with parameters that the installation should have recorded, there were no operational parameters relating to vertical forces, brake pressures, or autobrake usage.

The aircraft was also equipped with a Quick Access Recorder (QAR). This recorded the same data as the FDR and suffered the same parameter problems.

Recordings of radar and radio transmissions from East Midlands Airport were supplied to the AAIB.

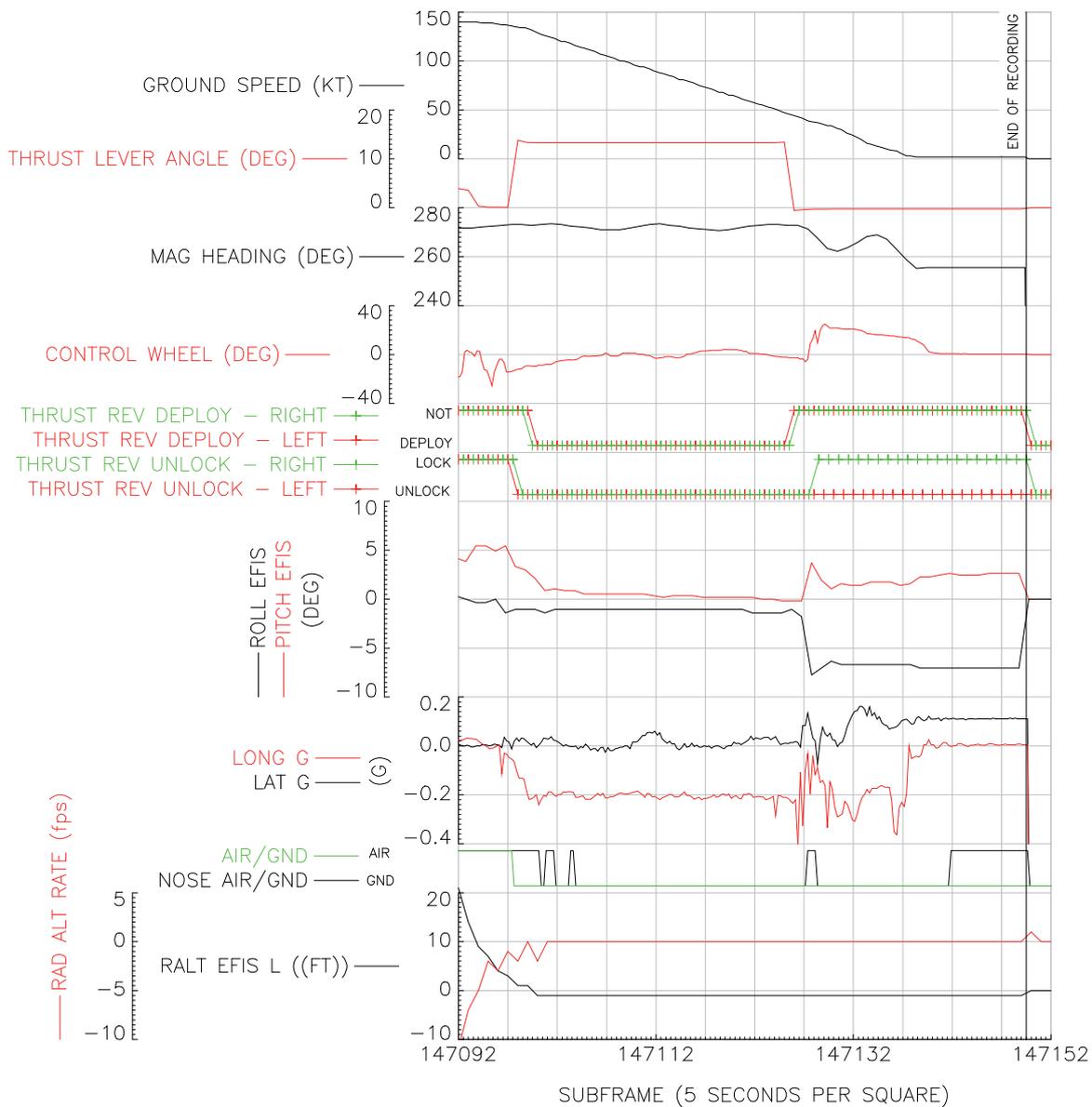


Figure 2
Pertinent FDR parameters

The aircraft took off at a recorded time of 0040:46 hrs and touched down at 0128:59 hrs. Figure 2 is a plot of the pertinent recorded parameters for the landing. There was no valid normal-acceleration parameter, but the derived closure rate with the runway does not indicate a heavy landing. The thrust reversers were deployed. There were no valid recorded brake-parameters but the longitudinal acceleration during the landing roll was very uniform. A brief spike in longitudinal acceleration was recorded as the aircraft groundspeed reduced through 52 kt. This was followed 2.25 seconds later by a larger spike in longitudinal acceleration and then oscillations with a frequency too high for the parameter to follow accurately. After approximately one second of these oscillations in longitudinal acceleration, a clockwise control wheel input was recorded, associated with a change in attitude which peaked at 7.7° left-wing-down and 3.7° nose-up pitch.

The aircraft slowed to a stop over the next 10 seconds with the longitudinal acceleration varying around the -0.2 g figure associated with the original period of steady braking. Shortly after the aircraft came to a stop, the master caution was triggered. Both the FDR and CVR recordings stopped approximately 11 seconds after the aircraft stopped. The last recorded attitude shows the aircraft stabilised at 7.0° left-wing-down and 2.6° nose-up pitch, with the nose gear weight on wheels sensor indicating AIR instead of GROUND.

The thrust reversers were recorded as 'not deployed' just before the onset of the longitudinal acceleration oscillations. This was followed by the right reversers registering the 'lock' state; however the left reversers remained in the 'unlock' state due to the aircraft resting on the engine.

Aircraft description

The Boeing 737-400 Series 476 is a low-wing, pressurised aircraft with retractable tricycle landing gear. The accident aircraft was manufactured in 1990 and operated in a passenger configuration on the Australian CAA register. Between November 2012 and February 2013, it was converted to SF (Special Freighter) configuration for its current operator, transferred to the Irish Aviation Authority (IAA) register and re-registered as EI-STD. During the conversion work the left and right main landing gears were replaced with recently overhauled units.

The aircraft held a valid Certificate of Registration and Airworthiness, issued by the IAA on 26 February 2013. Other than the inoperative flap load relief system, there were no significant defects recorded in the aircraft technical log.

Landing gear

The Boeing 737 landing gear consists of two MLG assemblies located inboard of each engine nacelle and aft of the rear spar and a nose gear assembly located below the aft bulkhead of the flight deck. All three assemblies are fitted with double wheels. Landing loads are taken on air-oil (oleo) shock absorbers within the landing gear struts and consist of an inner and outer cylinder constructed from high strength steel alloy. The outer cylinder is attached to retraction, drag and weight carrying struts. The bottom of

the outer cylinder incorporates a gland seal assembly through which the inner cylinder passes. The inner cylinder carries the axle, wheels and brake assemblies and its upper end is fitted with a sliding bearing assembly to maintain inner and outer cylinder concentricity. The two cylinders are prevented from rotating within each other by a torque link and anti-shimmy damper assembly.

The landing gear is retracted and lowered hydraulically, with a facility for emergency lowering by mechanical means. The gear is locked down by a hydro-mechanical folding strut mechanism. Both sets of mainwheels are fitted with multi-disc hydraulic brake units with antiskid protection, an autobraking system and a parking brake.

Autobrakes

The aircraft is equipped with an automatic braking system designed to relieve pilot workload. The system works in conjunction with the speed brake and antiskid system to provide braking with feet off the brake pedals during landing. The pilot can transfer from auto to manual braking at any time by depressing the brake pedals.

Damage to aircraft

The crew had just selected manual braking from autobrake during the latter stages of their landing rollout and heard the loud “bang” as the lower section of the left MLG detached. The aircraft tilted and continued to slow, veering left before coming to a gentle stop.

Marks and damage to the runway surface indicated that the aircraft had travelled 115 m with its weight on the left engine nacelle and left MLG outer cylinder, from the position where the left MLG had failed. A debris trail, consisting mainly of composite material, was deposited on the runway, along with a large oil stain where the MLG lower section had detached. The aircraft’s path described a gentle curve diverging to the left, away from the runway centreline. The aircraft had come to rest with its nosewheel off the ground and its weight borne on the right MLG, the remains of the left MLG and the underside of the left engine nacelle.

The left MLG inner cylinder had fractured through the chrome portion approximately 75 mm above the axle. The fracture was horizontally across the full diameter of the inner cylinder and exhibited a discoloured thumbnail-shaped feature on its surface. This feature was on the forward face of the MLG, approximately in line with the level at which the inner cylinder protrudes from the outer cylinder with aircraft weight on wheels. The upper torque link arm had failed and the antiskid system wiring harness, conduit and brake pipes had parted. The left mainwheels, brake units and axle assembly came to rest approximately 27 m behind the aircraft, to the left of the centreline.

The detached MLG tyres were found to be correctly inflated, but had cuts and abrasions in the sidewalls and on the tread.

Impact damage was sustained by the inboard edge of the left inboard flap and track rollers. The flap trailing edge was distorted and delaminated, exposing the internal

honeycomb structure and the mainplane composite trailing edge root fairing was holed, with a section missing. There was also evidence of tyre rubber scuffs on the flap, root fairing and fuselage in the vicinity of the damage. The left engine bypass duct and casing was damaged and the low pressure (LP) fan could not be rotated. Subsequent further inspection found the engine pylon was distorted on its mountings in the mainplane, although this relaxed and the LP fan became free to rotate as the aircraft was airbag-lifted during the salvage operation.

Tests and research

The remains of the left MLG were removed from the aircraft and, along with the detached axle and wheels, were recovered to the AAIB hangar at Farnborough for examination. The lower gland seal nut locking plate had abraded through as it travelled along the runway and the gland nut had been forced to rotate, tightening and jamming it in place. The wheels and brakes were removed from the axle and the inner cylinder tube was extracted by cutting the top from the outer cylinder because of the jammed gland nut. The inner cylinder guide bearings and locking collar were present, correctly assembled and undamaged. The wheel hubs, bearings, tyres and brake assemblies were inspected after disassembly and found to be undamaged and in good condition, except for running surface cuts and sidewall abrasions to the tyres. Dimensional checks were also carried out as far as possible, taking into consideration the possibility that the structures were distorted during runway abrasion and inner cylinder breakup.

High magnification visual examinations were initially carried out and microsections were prepared through the fracture in order to analyse the steel structure in the immediate vicinity using a scanning electron microscope (SEM). To examine the steel substrate surface further the chrome plating was chemically removed, so as not to cause additional mechanical damage to any features beneath the chrome.

Findings

The left MLG internal and external dimensions were found to be within acceptable tolerances, as detailed in the Boeing Component Maintenance Manual (CMM), despite the runway abrasion. Material conformity checks showed that the elemental composition of the inner cylinder was consistent with 4340M steel which was within the specified hardness limits. The chrome thickness on the lower section of the cylinder was 200-210 μm thick, compared to 160-170 μm at the upper section. The chrome met the required 16 micro-inch surface finish specified by the manufacturer.

The visual examination under magnification of the outer chrome plated surfaces of the inner cylinder revealed extensive crazing of the chrome plating. This phenomenon is known as 'chicken wire' cracking and was apparent over the majority of the surface. Small flakes of the crazed chrome plating had detached from the substrate material at the edge of the fracture face, leaving an imprint of the crazing in the form of ferrous oxide tracks (Figure 3).

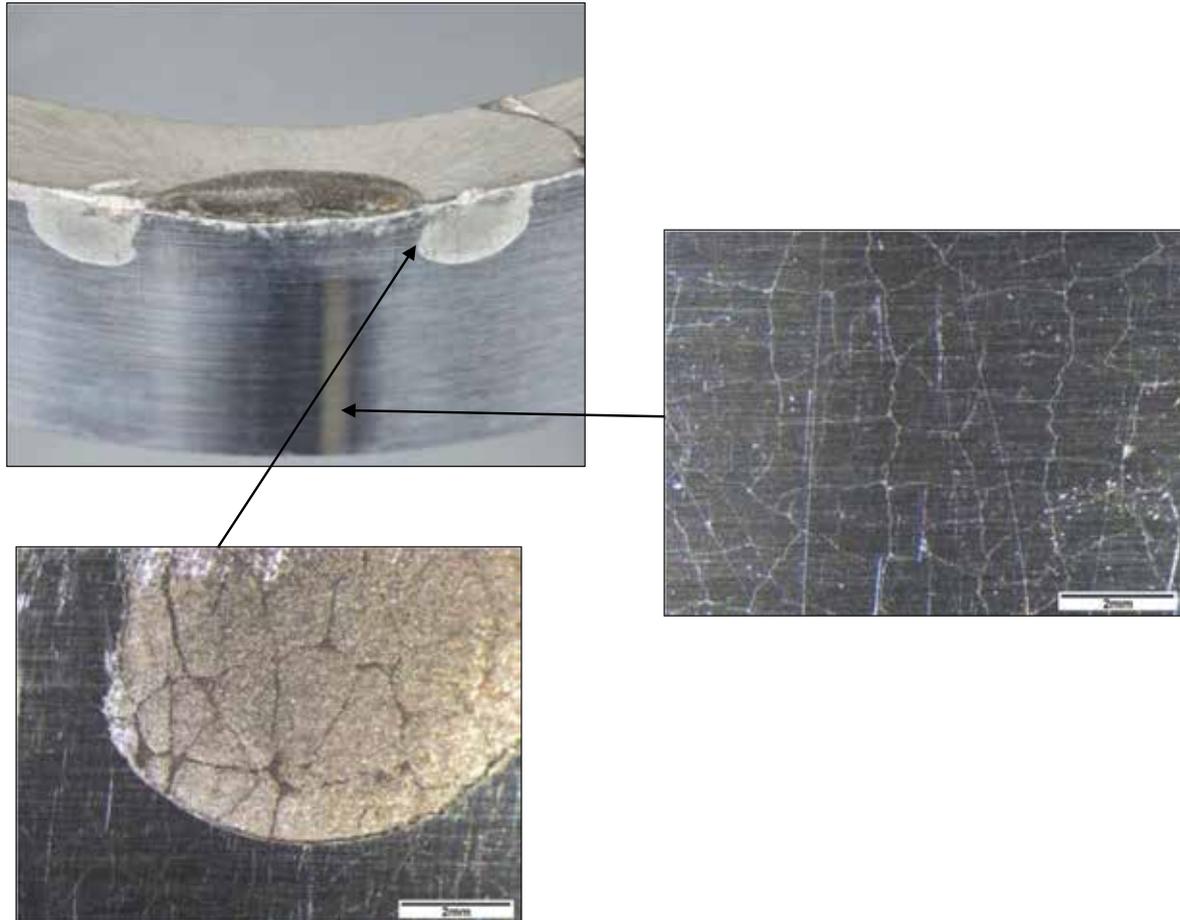


Figure 3

Chrome plate flake area and ferrous oxide tracks left by the chicken wire cracking

The fracture face showed three distinct failure mechanisms in the grey 'thumbnail' area of the fracture (Figure 4). The majority of this area exhibited stress corrosion. Further into the material there was evidence of fatigue and the remainder of the fracture face showed the characteristics of ductile overload.

As the investigation progressed it was also found that the ferrous oxide tracks on the substrate were present beneath the chrome which was exposed to the elements, but not on the upper area normally surrounded by oil in the outer cylinder.

The inner cylinder area above the fracture face on the portion of the cylinder which had been forced up into the outer cylinder during the runway abrasion exhibited circumferential helical bands in the chrome plate. When the chrome was removed, these marks were also present on the steel substrate. Metallurgical analysis revealed localised heating damage correlating to the bands.

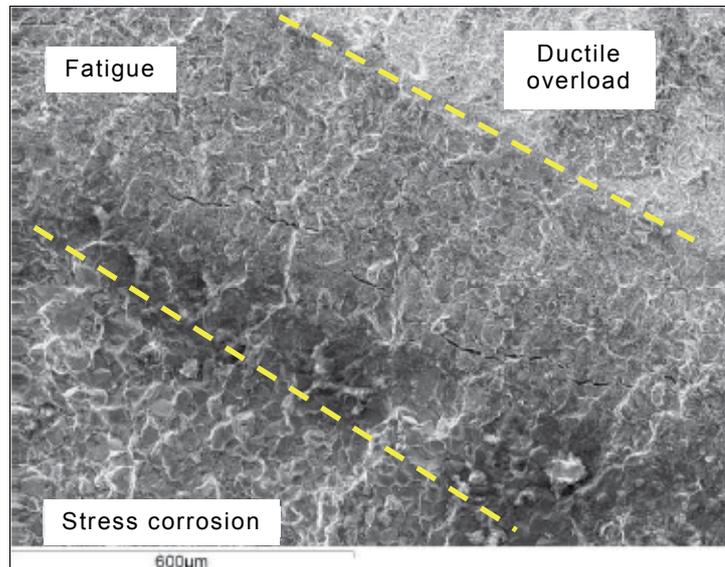
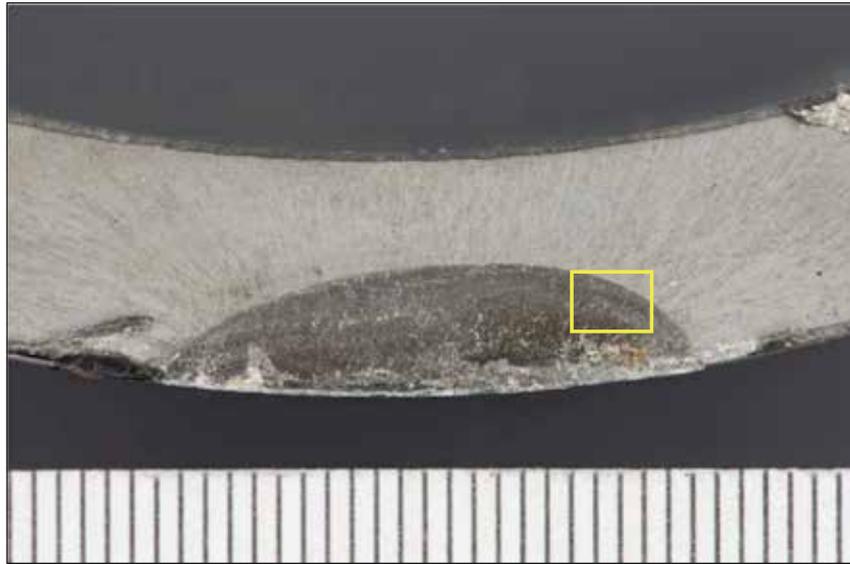


Figure 4
Fracture surface map

With the chrome plating removed, a very distinctive area of ferrous oxidation became apparent on the surface of the steel, just beneath the area of fatigue cracking (Figure 5). In addition, in the same area, there was also evidence of chrome combining with the steel.

Metallurgical examination of the microsection through the fracture face showed an area in the substrate steel of over and undertempered martensite, consistent with localised heating. The hardness profile through this section also confirmed this finding. Prior to removal of the chrome, hardness checks were carried out; these showed that the chrome decreased in hardness in the vicinity of the fracture face. Figure 6 shows the disposition of the martensite.

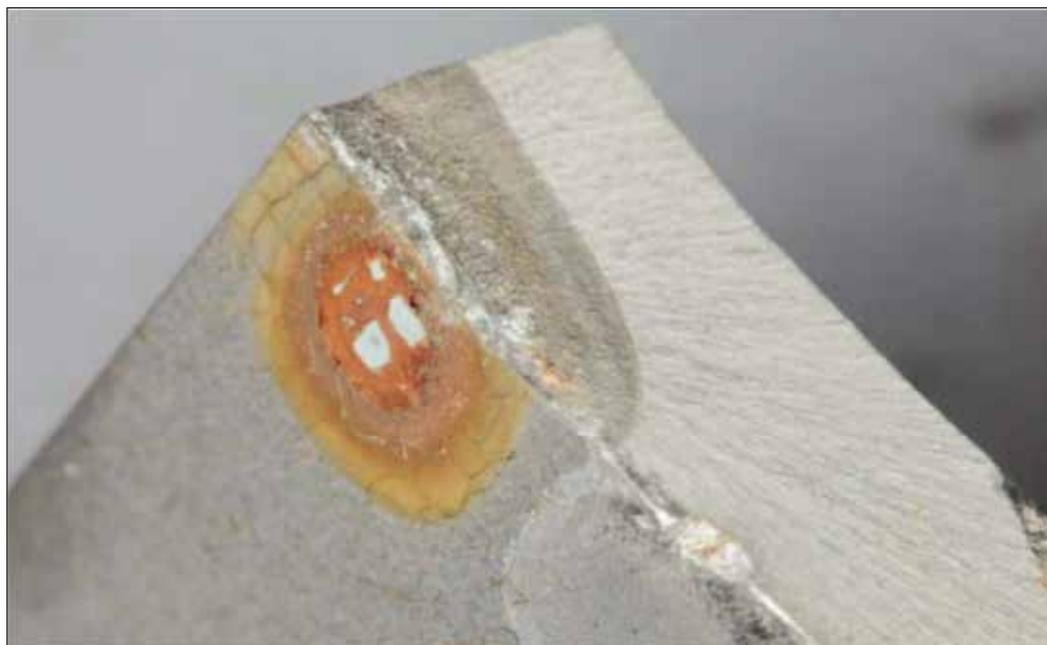


Figure 5

Ferrous oxidation on the substrate beneath the chrome plating
(after longitudinal microsection)

The features linked to the fracture face and the helical banding were the only places on the inner cylinder steel substrate which showed localised heating. Areas of the steel substrate away from the fracture face, banding and with an absence of ferrous oxide chicken wire tracks showed no evidence of heating or material distress.

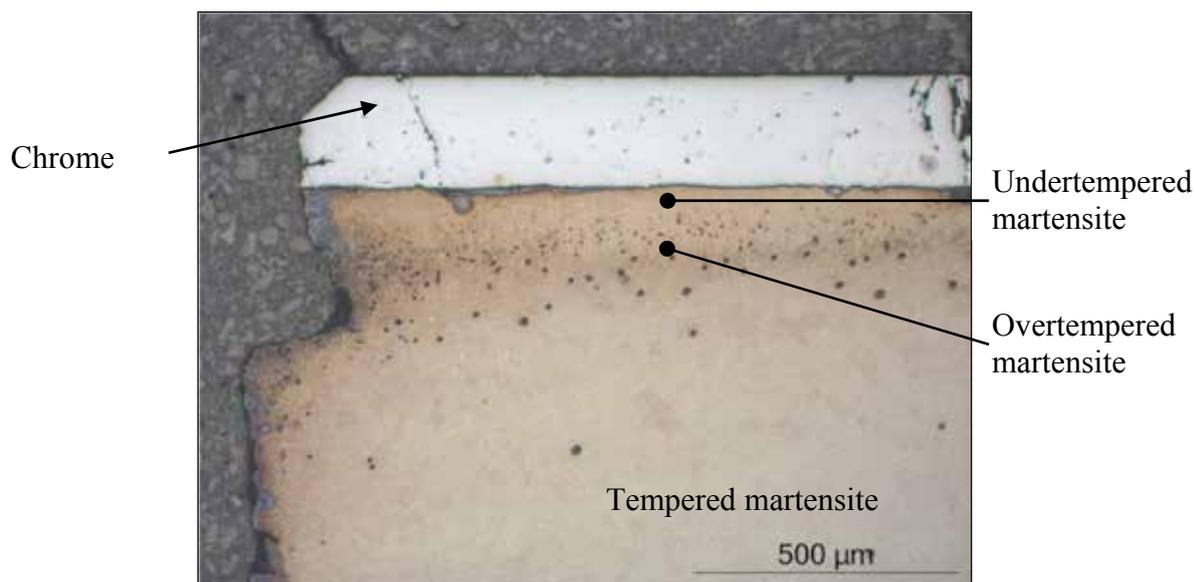


Figure 6

Fracture surface metallurgy

MLG history

The left MLG assembly was overhauled between December 2012 and the end of January 2013 and released to service on FAA Forms 8130-3, dated 23 & 25 January 2013. The work included re-chrome plating and refinishing of the inner cylinder which was carried out in accordance with Boeing CMM 32-11-11 Revision 109, dated 1 November 2012. Since installation on EI-STD during conversion to freighter, the MLG had accrued 878 landing cycles. The most recent maintenance on the MLG was task B32-10-00-A-1, a visual check of oleo/drag/side struts and associated hardware for condition and security of installation. This was a 500-cycle repeat inspection and was carried out 27 April 2014 on a 2A Check at 41,344 aircraft cycles. The aircraft had accrued a further 3 cycles by the time of the accident on 29 April 2014.

Since conversion there were no significant events recorded against the MLG, wheels or brake assemblies.

Additional observations

During the on-site examination of the aircraft it was found that the antiskid wiring loom connecting socket had parted between the connector shell and conduit union, with no apparent damage to screw threads. The shell was attached to the airframe portion of the connector, its three cables having been pulled out of the seal gland and connecting pins. Further examination showed that the connecting socket had parted under the tensile load applied on its protective conduit at the point when the MLG inner cylinder separated. Under magnification, very minor damage was apparent on approximately 25% circumference of the single male start thread of the aluminium alloy connector shell. The conduit steel female union was undamaged. This minimal damage to the thread implied that the shell and conduit union were attached by less than one thread.

The right MLG antiskid conduit and connector was inspected and found to be intact, but the connector shell and conduit union also appeared engaged only by a single thread.

The connector and conduit union was visually examined on another Boeing 737 aircraft and found to be fully threaded together on both sides of the aircraft. It is therefore considered to be an anomaly in the case of EI-STD.

Although an unsatisfactory assembly condition, found on the post-accident examination, it had no effect on the operation of the aircraft braking system and therefore had no bearing on the accident.

Analysis

Operational aspects

The landing was unremarkable until the commander's brake pedal applications to disconnect the autobrake. The recorded data showed that these applications were of normal magnitude, and did not contribute to the failure of the landing gear leg.

Engineering aspects

Wheel and axle detachment

The brake pedal application to deselect the autobrake is likely to have imparted a short duration increased drag load to both MLG. This load was not excessive, but was enough to overload the already weakened structure of the left MLG inner cylinder. The braking load would have created a bending moment on the inner cylinder putting the material at the leading face of the inner cylinder, at the point where it protrudes from the outer cylinder, under tension in the vicinity of the stress corrosion cracking.

The axle, wheels and brakes assembly is of substantial weight and, after inner cylinder fracture, would have been partially restrained momentarily by the torque links, brake pipes and electrical harnesses. Although there were no witnesses to observe the separation of the MLG axle and wheel assembly, damage to the flap and fuselage fairings and the damage to the ancillary components is consistent with detachment being violent and rapid. It was noted that the wheels and tyres had protected the fracture face; their size and position prevented the fracture surface from contacting other parts of the aircraft or the runway, therefore leaving unadulterated metallurgical evidence.

Recent inspection

Daily MLG checks and the inspection carried out two days before the accident did not reveal any defects with the MLG. Whilst chicken wire cracking can in some circumstances be seen with the naked eye, it is very difficult to detect without significant magnification and a suitable light source held at a suitable angle. It is even more difficult to detect in situ because only a relatively small portion of the inner cylinder chrome surface is visible with the aircraft weight on wheels and this area is usually covered in oil residue, brake and runway dust and grit. It is therefore not surprising that the cracking was not detected prior to the accident.

Metallurgical findings

The forensic examination of the fracture face identified stress corrosion cracking, fatigue and ductile overload failure mechanisms. The small areas of chrome plate at the centre of the ferrous oxidation had resisted the electro-chemical removal process. The reason for this was that the corrosion beneath the chrome was severe enough not to allow electrical continuity between the steel substrate and the chrome, thus inhibiting the process. This indicates that this was the most probable position where the corrosion and therefore damage was most severe and the most likely initiator of the stress corrosion cracking in the steel substrate leading to the fatigue failure. It is possible that damage was as a result of very high temperature localised heating of the chrome plated surface which also affected the substrate beneath. This scenario is supported by the presence of the martensitic area in the substrate steel as shown by the examination after microsection through the fracture surface. However, this is the only area of localised heat damage other than the helical banding. Therefore, it can be concluded that the chicken wire cracking is likely to have been caused by a grinding anomaly during the finishing process, but that it was not severe enough to impart heat damage into the steel substrate. The

source of the heat which caused the damage to the steel substrate could not be identified with any degree of certainty.

Conclusions

The damage to the flap system, fuselage, and MLG equipment was attributable to the detachment of the left MLG axle, wheel and brake assembly. The damage to the MLG outer cylinder, engine and nacelle was as result of the aircraft settling and sliding along the runway.

The left MLG axle assembly detached from the inner cylinder due to the momentary increase in bending load during the transition from auto to manual braking. The failure was as a result of stress corrosion cracking and fatigue weakening the high strength steel substrate at a point approximately 75 mm above the axle.

It is likely that some degree of heat damage was sustained by the inner cylinder during the overhaul process, as indicated by the presence of chicken wire cracking within the chrome plating over the majority of its surface. However, this was not severe enough to have damaged the steel substrate and therefore may have been coincidental. Although the risk of heat damage occurring during complex landing gear plating and refinishing processes is well understood and therefore mitigated by the manufacturers and overhaul agencies, damage during the most recent refinishing process cannot be discounted.

The origin of the failure was an area of intense, but very localised heating, which damaged the chrome protection and changed the metallurgy; ie the formation of martensite within the steel substrate. This resulted in a surface corrosion pit, which, along with the metallurgical change, led to stress corrosion cracking, fatigue propagation and the eventual failure of the inner cylinder under normal loading.

Safety actions

Although it is not clear how or when the chrome plating damage occurred, the landing gear overhaul company has carried out a comprehensive review of their processes as a precaution.

The airport operator issued a safety bulletin to air traffic controllers reminding them of emergency communications protocols and procedures, undertook a review of internal emergency communications procedures, and planned investment in new communications equipment, in order to enable better and more automated communications.