Australian Government
Australian Transport Safety Bureau

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AVIATION SAFETY INVESTIGATION REPORT
200205780

In-flight uncontained engine failure and air turn-back, Boeing 767-219ER, ZK-NBC

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INTRODUCTION

The Australian Transport Safety Bureau (ATSB) is an operationally independent multi-modal Bureau within the Commonwealth Department of Transport and Regional Services. ATSB investigations are independent of regulatory, operator or other external bodies.

In terms of aviation, the ATSB is responsible for investigating accidents, serious incidents, incidents and safety deficiencies involving civil aircraft operations in Australia, as well as participating in overseas investigations of accidents and serious incidents involving Australian registered aircraft. The ATSB also conducts investigations and studies of the aviation system to identify underlying factors and trends that have the potential to adversely affect safety. A primary concern is the safety of commercial air transport, with particular regard to fare-paying passenger operations.

At the time of the occurrence in question, the ATSB performed its aviation functions in accordance with the provisions of the *Air Navigation Act 1920*, Part 2A. Section 19CA of the Act states that the object of investigation is to determine the circumstances surrounding any accident, serious incident, incident or safety deficiency to prevent the occurrence of other similar events. The results of these determinations form the basis for safety recommendations and advisory notices, statistical analyses, research, safety studies and ultimately accident prevention programs. As with equivalent overseas organisations, the ATSB has no power to implement its recommendations.

It is not the object of an investigation to determine blame or liability. However, it should be recognised that an investigation report must include factual material of sufficient weight to support the analysis and conclusions reached. That material will at times contain information reflecting on the performance of individuals and organisations, and how their actions may have contributed to the outcomes of the matter under investigation. At all times the ATSB endeavours to balance the use of material that could imply adverse comment, with the need to properly explain what happened, and why, in a fair and unbiased manner.

The 24-hour clock is used in this report to describe the Brisbane local time of day, Eastern Standard Time (EST), as particular events occurred. Eastern Standard Time was Coordinated Universal Time (UTC) + 10 hours. Times are accurate to within 30 seconds of the reported event.

EXECUTIVE SUMMARY

Approximately six minutes after take-off from Brisbane, Australia on a scheduled passenger service to Auckland, New Zealand, the Boeing 767-219ER aircraft, registered ZK-NBC sustained an uncontained failure of the left (number-1) engine, necessitating a return to Brisbane.

During the return, the flight crew elected to conduct a prepared emergency landing, however communication misunderstandings between the flight crew and the cabin in-flight service director (ISD) resulted in some crew and passengers not being appropriately briefed. The flight crew's subsequent call for the 'brace' position at 500 ft thus came as a surprise to the unaware cabin crew, some of whom adopted the unprepared emergency landing procedures, calling "Emergency - grab your ankles" to the passengers.

Failure of the number-1 engine (a General Electric CF6-80A high-bypass turbofan engine) resulted from the fracture and liberation of a large segment from the first-stage high-pressure turbine disk. The disk failure initiated from a radial fatigue crack at the base of a turbine blade slot, one of three similar cracks that were found during the subsequent investigation. The loss of the disk segment, the resultant imbalance and rapid engine seizure produced extensive damage to the engine casing, accessory components and the engine pylon. The released disk segment impacted the leading edge flap panel immediately above the engine – damaging a 600mm length and resulting in the flight crew electing not to use the leading edge flaps for the return approach and landing at Brisbane. Because the engine pylon and leading edge flap damage sustained during the engine failure was likely to affect the structural strength of the engine pylon and the performance and flight characteristics of the aircraft, the event was classified as an accident, in accordance with the definition published by the International Civil Aviation Organization (ICAO) in Annex 13 to the Convention on International Civil Aviation.

ATSB laboratory examination found that the disk cracking had originated from the rear break-edge corner of the blade fir-tree slots; an area that had sustained heavy surface microstructural damage as a product of manufacturing and/or repair shot peening processes. While subsequent fatigue testing of other blade slots with similar surface damage did not conclusively identify a loss of fatigue life resulting from the peening processes, it is known that overly heavy or abusive shot peening can prove detrimental to fatigue performance.

As a result of the findings of the investigation, the engine manufacturer has implemented several changes to the manufacturing and repair shot peening processes, to avoid the surface damage found on the failed disk. Other safety action taken included revising the inspection requirements for the CF6-80A disks to include the more thorough examination of the slot bottom and rear break-edge areas, as required for the CF6-80C series engines. The US Federal Aviation Administration (FAA) and the Australian Civil Aviation Safety Authority (CASA) have subsequently mandated the revised requirements. The aircraft operator, as part of its own investigation into the occurrence, has developed a series of recommendations aimed at addressing the crew communication deficiencies experienced during the return to Brisbane after the engine failure.

1 FACTUAL INFORMATION

1.1 History of the flight

At 1012 Eastern Standard Time (EST) on 8 December 2002, the Boeing 767-219ER aircraft, registered ZK-NBC, departed Brisbane, Australia on a scheduled passenger service to Auckland, New Zealand. Approximately six minutes into the flight, while climbing through flight level 110 (FL110), the crew reported a loud 'bang' on the left side of the aircraft and felt the aircraft 'lurch' to the right, followed by a progressive yaw to the left. After checking instrumentation, the failure of the left (number-1) engine was confirmed and the engine was shut down in accordance with the *Engine Fire, Severe Damage or Separation* checklist from the aircraft quick-reference handbook (QRH). The co-pilot declared a full emergency to Brisbane air-traffic control and was given a radar track and clearance for a direct return to Brisbane aerodrome. Reports from the cabin crew to the flight crew indicated that the left engine had sustained severe damage to the nacelle and a subsequent inspection by a flight crewmember found damage to the wing leading-edge flaps. In consideration of the flap damage, the flight crew elected to carry out the approach without the leading-edge flaps and using limited trailing-edge flap extension. While the flight crew discussed the flap damage, a clearance was obtained to hold the aircraft to the south of the airport at 4,000 ft until preparations were made. At 500 ft on the final approach, a 'brace' command was made to the passengers and cabin crew. The aircraft used the full length of runway 01 for the landing roll, turning onto the end taxiway (taxiway alpha) and was attended by rescue and fire fighting service (RFFS) vehicles. Due to the extent of damage to the left engine and part of the forward cowling dragging on the ground, the crew elected to shut the remaining engine down on the taxiway and disembark the passengers at that point.

Event summary:

1012	Flight departed Brisbane
~1018	Engine failure
1020	Emergency declared
1043	Flight landed in Brisbane
1048	Emergency cancelled by RFFS
1049	Runway 01 closed due to debris
1054	Runway 01 reopened
1055	ATSB notified

1.2 Injuries to persons

Injuries	Crew	Passengers	Others	Total
Fatal				
Serious				
Minor				
None	10	190		200

1.3 Damage to the aircraft

The aircraft sustained damage to the number-one engine and nacelle assembly and the structure around the engine, including the pylon, the number-5 leading edge flap and the number-2 flap canoe fairing. The engine outboard core cowl had ruptured through a large area within the upper panels, revealing extensive mechanical and structural damage to the turbine section. A section of the first-stage high-pressure turbine disk had been liberated from that section of the engine and was not recovered.

1.3.1 Damage to the airframe

The primary airframe damage was sustained by the engine pylon and the leading edge flap structure immediately outboard of the pylon (figure 1). The left side pylon fairings exhibited a heavy gouge leading vertically upward from the nacelle to the damaged wing leading edge flap (figure 2), the dimensions of the gouge indicating that it was probably produced by the liberated disk segment. The wing leading edge flap skin was extensively torn over a length of approximately 600 mm, with extensive pitting and indentation of the surrounding surfaces from the smaller debris liberated when the disk failed (figure 3). Prominent distortion of the pylon structure was evident externally as buckling and distortion of the adjacent wing underside panels (figure 4). As a result of the discovery of that damage, the operator commissioned a structural condition survey of the pylon and wing structure[1], which confirmed that the pylon had sustained twisting and buckling damage due to the rapid stopping torque applied during the engine failure. The survey also determined that the damage was confined to the pylon structure, with the adjoining wing box not sustaining any significant damage.

Fig. 1 Overview of the damage sustained by the left engine and wing leading edge of ZK-NBC

[1] Air New Zealand Engineering Services, Boeing 767-219 Aircraft ZK-NBC Left hand Engine Incident Structural Condition Report TR 9000435-Rev:00

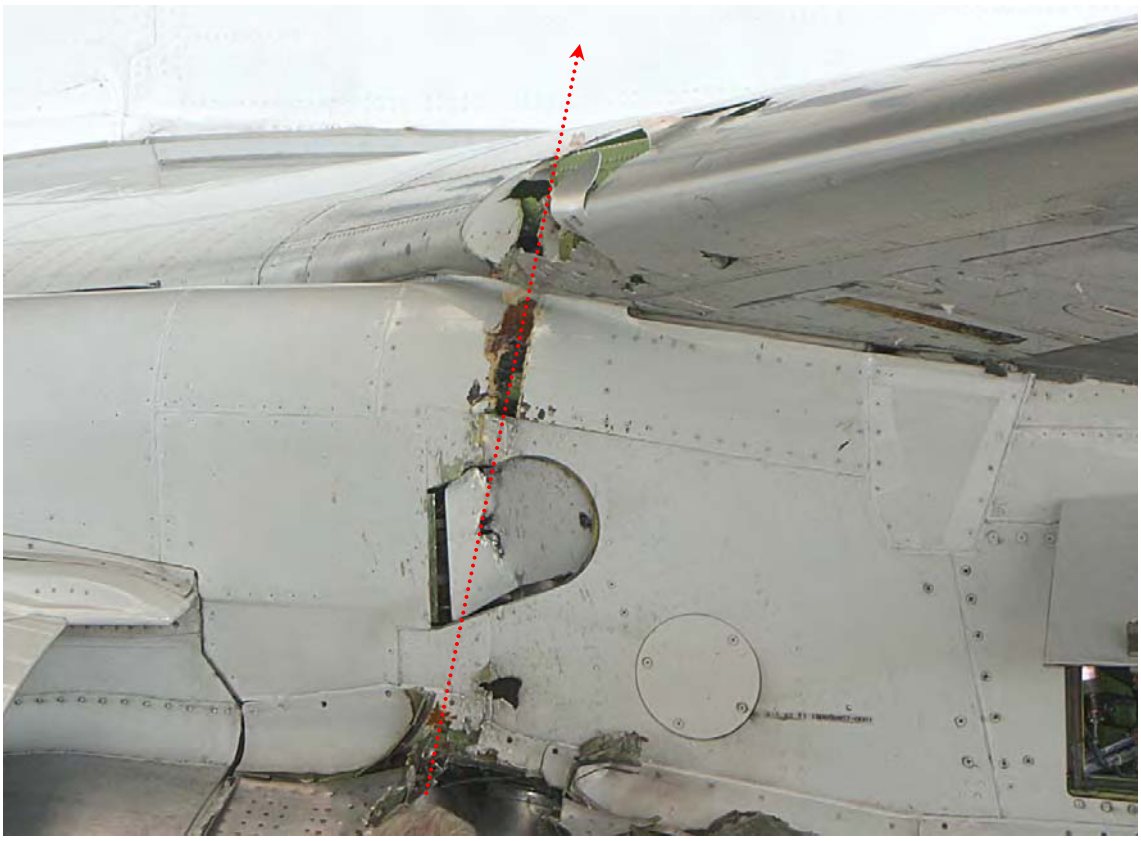

Fig. 2 Vertical gouge in the engine pylon fairings – likely produced by the liberated segment of high-pressure turbine disk. The dotted line illustrates the likely trajectory of the disk fragment.

Fig. 3 Damage to the wing leading edge profile above the engine core rupture.

Fig. 4 Lateral distortion and crushing of the wing and pylon fairings, suggesting mechanical distortion of the pylon structure.

1.3.2 Damage to the engine and nacelle

The ATSB carried out a general inspection of the failed engine before it was removed from the aircraft. The engine exhibited an explosive rupture in the outboard core cowling and partial loss of the fan cowling panels. Beneath the cowling, the engine revealed extensive mechanical damage to the core casing, ducting and wiring around the plane of the first-stage high-pressure turbine rotor. Some melting and charring of wiring and insulation was noted around the core, however there was no evidence of a sustained fire. Through the severed casing, it was apparent that a section had separated from the first-stage high-pressure turbine disk (HPT1) and passed through the casing, producing the engine and airframe damage evident externally. A summary of the engine damage and an analysis of the failed turbine disk was conducted by the ATSB and is detailed in attachment A.

1.4 Aircraft information

Manufacturer	Boeing Commercial Aircraft Group
Model	767-219ER
Serial number	23328
Registration	ZK-NBC
Airworthiness certification	FAR Part 25, Transport Category Airplanes
Year of manufacture	1986
Total airframe cycles	20,390
Total airframe hours	68,007
Allowable landing weight	126,098 kg
Actual landing weight	129,700 kg

1.5 Engine information

The aircraft was powered by two General Electric CF6-80A high-bypass turbofan engines. The failed engine (serial number 580-110) had operated for a total of 35,136 hours and 11,187 cycles since manufacture, with the last 2,086 hours and 772 cycles while fitted to ZK-NBC. The engine was last overhauled in August 1998 at a life of 21,196 hours / 6,287 cycles and the last off-wing repair was carried out in August 2001 as a result of excessive high-speed spool (N2) vibrations. Technical Analysis report number 19/03 (attachment A) summarises the history of the engine and details the life of the failed high-pressure turbine disk.

1.6 Personnel information

The aircraft carried an operational flight crew of three, consisting of the pilot in command, a co-pilot undergoing an operational currency check and a supplementary pilot required for the check flight. Seven cabin crew were on-duty during the flight, headed by an Inflight Service Director (ISD). Following the engine failure, a representative of the New Zealand Transport Accident Investigation Commission, being the accredited representative for the State of the aircraft operator, conducted interviews with the flight crew and the ISD. In all cases, the crew were found to be properly licensed and medically fit to conduct the flight.

1.7 Cabin events and management

1.7.1 Emergency landing procedures

The operator's procedures for a prepared emergency landing required the flight crew to call the ISD to the flight deck, using the cabin public address (PA) system. Once appraised of the flight crew's requirements, the ISD was to return to the cabin and inform other cabin crew, who then make the necessary preparations and instruct passengers on how and when to take up the brace position. When the "Brace-Brace-Brace" command is made from the flight deck, procedures required the cabin crew to call "Heads down-stay down".

In the event of a sudden, unexpected emergency, the operator's procedures required the cabin crew to call "Emergency – grab your ankles". The intention of that instruction was to have passengers bending over in a position to reduce flailing and other injuries, when insufficient time was available to have passengers properly prepared for a brace instruction.

1.7.2 Cabin events

After hearing the loud bang associated with the engine failure, the cabin crewmember designated FA3 (Flight Attendant position 3) reported looking through a window near the over wing exits and observing significant damage to the left engine. He went forward to advise the ISD, who had contacted the flight deck by interphone immediately after the event. The ISD asked the cabin crewmember to report the damage directly to the flight crew.

The ISD reported hearing several PA announcements from the flight deck, advising the passengers of the engine failure and the intention to return to Brisbane. The ISD was

subsequently briefed by the flight crew with general information regarding the failure and the return to Brisbane. He later received an interphone call from the flight crew advising of the intention to relay a 'brace' instruction at 500ft in the landing approach. The ISD stated that the interphone call had been brief and he did not properly hear the message regarding the 'brace' instruction. FA3, at the over wing exits had picked up the interphone at the same time as the ISD and had heard the message to the ISD. FA3 subsequently told the cabin crewmember seated next to him that there would be a 'brace' instruction at 500ft, however that was not communicated to any other crewmember.

The ISD reported that he was about to contact the flight crew regarding the misheard message when he heard a PA announcement "Five hundred feet. Brace Brace Brace". The two cabin crewmembers at the over-wing exits, who were the only cabin crew expecting the 'brace' call, immediately issued the *prepared* emergency brace command "Heads down – stay down". The ISD and some of the other cabin crew, being surprised by the call, shouted the *unprepared* emergency command "Emergency – grab your ankles". Some of the cabin crew did not make any calls, however they reported that the passengers were following the shouted commands from the other crew. The ISD reported that the passengers generally remained calm after the brace call, although some were upset and alarmed by the unexpected nature of the alert.

1.7.3 Flight deck events

After receiving notification of the engine damage from the cabin crew, the pilot in command asked the supplementary pilot to inspect the damage personally. The flight crew then discussed the appropriate actions for the cabin and decided that due to the damage to the leading edge flaps and the required high landing speed, *prepared* emergency landing procedures were appropriate. The flight crew recalled that the supplementary pilot had communicated that intention to the ISD by interphone, however the defined procedure of calling the ISD to the flight deck was not followed. Before the landing, the pilot in command advised the passengers of the situation and that emergency services vehicles would attend the aircraft. He did not however, inform the passengers that there would be an "emergency landing" of any nature.

Upon reaching five hundred feet and making the 'brace' command, the flight crew reported being surprised to hear some of the cabin crew calling to the passengers "Emergency – grab your ankles" – the procedural commands used in the event of an *unprepared* emergency landing.

After the aircraft landed and vacated the runway, the flight crew shut down the right engine after advice from RFFS that loose cowling sections from the left engine were dragging on the taxiway. Reports from the RFFS of smoke emanating from the main landing gear brakes prompted the flight crew to request the ISD to ensure that the cabin was ready, with door slides armed for a possible evacuation.

1.8 Recorded information

1.8.1 On-board recorders

The aircraft was fitted with an AlliedSignal solid-state universal flight data recorder (SSUFDR) and an AlliedSignal solid-state cockpit voice recorder (SSCVR). Following the occurrence, both units were removed from the aircraft and a copy of the recorded data and audio was made by the ATSB. The aircraft was not fitted with a quick-access

recorder. The recovered data from the SSUFDR was used to prepare a summary of events and actions during the flight. Copies of the aircraft's Engine Indication and Crew Alerting System (EICAS) exception pages were used to supplement the recorder data.

1.8.1.1 Cockpit voice recordings

The SSCVR contained four channels of audio information with a nominal duration of thirty minutes per channel. An initial review of the recorded audio from each channel found evidence that the recorder had continued operating for an undefined period following the occurrence and the subsequent flight turn-back and landing in Brisbane. As a result, the recording contained only post-flight ambient noise and sounds typical of ground personnel performing maintenance on the aircraft.

The aircraft operator had a standard operating procedure (SOP) that required the flight crew to remove power from the CVR upon the completion of any flight during which an incident might have occurred. While that procedure was performed after the flight crew had secured the aircraft, the elapsed time following the event resulted in the over-writing of the recorded audio.

1.8.1.2 Flight data recordings

The aircraft's SSUFDR contained 27.2 hours of data, comprising the accident flight and seven complete previous flights. The complete data set was analysed using the bureau's Recovery, Analysis and Presentation System (RAPS) software.

The following sequence of events was developed from the flight data read-out.

Local Time (EST) (hh mm:ss)	**Event**
10:11:34	ZK-NBC stationary on runway with left engine N1 (Fan speed) = 93.8%, N2 (Core speed) = 100.1% and right engine N1 (Fan speed) = 97.4%, N2 (Core speed) = 101.9%. Left engine vibration (HPT) ≈ 0.6 units. Right engine vibration (HPT) = 0.48 units. EGT Left/ Right = 702°C/ 725°C.
10:11:35	ZK-NBC commences takeoff roll along Runway 01 at Brisbane Aerodrome. N1 (Fan speed) and N2 (Core speed) of both engines increase as thrust lever angle increased. EGT Left/ Right = 755°C/ 725°C.
10:11:47	ZK-NBC accelerating along runway, computed airspeed = 90 kts. Left engine vibration increased to 1.9 units (LPT) while right engine vibration stable ≈ 0.5 units (LPT). N1 (Fan speed) ≈ 102%, N2 (Core speed) ≈ 103%. EGT Left/ Right = 844°C/ 836°C.
10:11:57	Computed airspeed = 135kts. Left engine vibration = 2.02 units (LPT) while right engine vibration = 0.5 units (LPT). N1 (Fan speed) ≈ 101%, N2 (Core speed) ≈ 103%.EGT Left/ Right = 851°C/ 843°C.
10:12:07	ZK-NBC lifts off from Runway 01 at Brisbane Aerodrome and commences climb. Left engine vibration = 1.7 units (LPT) while right engine vibration = 0.44 units (LPT). N1 (Fan speed) ≈ 101%, N2 (Core speed) ≈ 103%. EGT Left/

	Right = 852°C/ 845°C.
10:14:51	ZK-NBC attains a south-easterly track while climbing through an altitude of 5,202 ft. Left engine vibration = 2.04 units (LPT) while right engine vibration = 0.69 units (LPT). N1 (Fan speed) ≈ 100%, N2 (Core speed) ≈ 102%. EGT Left/ Right = 815°C/ 813°C.
10:17:23	Aircraft climbing through altitude of 9,765 ft. Left engine vibration reaches maximum flight value = 2.12 units (LPT) while right engine vibration = 0.50 units (LPT). N1 (Fan speed) ≈ 102%, N2 (Core speed) ≈ 104%. EGT Left/ Right = 826°C/ 825°C.
10:17:27	Altitude = 9,947 ft, computed airspeed = 360 kts. Left engine vibration = 2.02 units (LPT) while right engine vibration = 0.42 units (Broad Band). N1 (Fan speed) ≈ 102%, N2 (Core speed) ≈ 104%. EGT Left/ Right = 827°C/ 826°C.
10:17:28	Altitude = 9,995 ft, computed airspeed = 360 kts. Left engine vibration = 2.02 units (LPT). N1 (Fan speed) ≈ 102%, N2 (Core speed) ≈ 104%. EGT Left/ Right = 827°C/ 826°C. FDR data unreliable or not recorded for last 0.25 second.
10:17:29	FDR data unreliable for first 0.125 second. An increase in lateral acceleration to the right was recorded for the first sample of this second before acceleration to the left. A/P CMD L disengaged, computed airspeed = 361 kts. Slight increase in left roll (0.4 degrees) and aircraft heading change to the left by 1.1 degrees. Left engine vibration reduced to 0.9 units while other left engine parameters were unreliable.
10:17:30	Altitude = 10,087 ft, computed airspeed = 357 kts. Left bank increases to 2.8 degrees and aircraft yaws a further 1.1 degrees to the left. Left engine vibration = 0.12 units (Broad Band) while right engine vibration = 0 units (Broad Band). Left Engine N1 (Fan speed) ≈ 41%, N2 (Core speed) ≈ 11%. Right Engine N1 (Fan speed) ≈ 101%, N2 (Core speed) ≈ 103%. EGT Left/ Right = 620°C/ 821°C.
10:17:37	Altitude = 10,413 ft, computed airspeed = 345 kts. Left engine shutdown with fuel flow reduced to zero. Left engine vibration = 1.18 units.
10:18:56	Altitude = 11, 717 ft, computed airspeed = 301 kts, left engine vibration = 0.32 units (Broad Band). A/P CMD L engaged and descent commenced.
10:25:26	Aircraft levels off at 3,930 ft.
10:37:47	ZK-NBC commences final descent and approach to Brisbane Aerodrome.
10:42:52	ZK-NBC touches down on Brisbane runway 01.

Figures 1 – 5 in the appendix present a selection of engine and aircraft parameters in graphical format that illustrate the events associated with the engine failure.

A comparative examination of the FDR data from the aircraft's seven previous flights showed the characteristic vibration levels from the left engine to have consistently exceeded the levels from the right engine by approximately an order of magnitude; the source being predominantly the low-pressure compressor (fan). Despite the discrepancies between engines, the recorded vibration levels from the left engine were

within the engine manufacturer's prescribed limits for the low-pressure compressor[2] and were not cause for maintenance action.

1.8.2 ACARS information

The 767-219ER aircraft employed an automated aircraft communications addressing and reporting system (ACARS) for in-flight condition monitoring, information exchange and aircraft performance assessment. The ACARS consisted of information processing and radio telemetry sub-systems interfaced with the flight data acquisition unit aboard the aircraft. Encoded messages were generated automatically by the system and transmitted to ground based receiving stations, where the relevant messages were assessed and formed part of the maintenance watch[3] for the aircraft.

Copies of the aircraft generated ACARS reports from the accident flight and the exceedence reports[4] for three months leading up to the event were obtained from the operator and evaluated in conjunction with the FDR data. With the exception of the reports stemming from the engine failure event, all of the exceedence reports received in that period were from the vibration monitoring system of the left engine. Fifty-nine reports, covering forty-six flights were received, with the majority (86%) citing the engine 'fan' (low-pressure compressor) as the dominant vibration source. A comparison of the last two ACARS vibration reports and the respective data carried by the FDR found the two data sets in general agreement with respect to the vibration magnitude and source.

1.9 Tests and research

The ATSB examined the failed high-pressure turbine disk (S/N: MPOP8478), assisted by authorised representatives from the engine manufacturer. On completion of that examination, the disk was conveyed to the engine manufacturer's laboratories in the US, where it underwent further detailed evaluation. A report detailing the findings of that examination was provided to the ATSB.

Failure of the turbine disk resulted from the growth of a fatigue crack from the bottom of a turbine blade fir-tree slot. Fatigue cracking had initiated at the rear corner of that blade slot and propagated radially into the disk body. Although intersecting one of the disk rim bolt holes, the cracking continued into the disk section, reaching critical size at a depth of approximately 39 mm and initiating overload failure of the remaining section and the release of the disk section.

Preliminary examination of the failed disk found two additional fir-tree slot bottom cracks, all extending from the slot bottom rear corners. Independent metallurgical evaluation by the ATSB, and subsequently by the engine manufacturer, determined that all of the cracks had similar fracture morphologies and all had initiated from areas that were free from material anomalies or isolated defects such as tool marks. Surface damage stemming from the production and/or repair shot peening processes was identified in the areas of fatigue crack initiation, as well as other rear slot bottom corner

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[2] At the time of the engine failure, the engine manufacturer's maintenance guidelines for the low pressure compressor (fan, N1) vibration indicated that no maintenance action was required for vibration levels less than 4.0 units.

[3] 'Maintenance Watch' – a coordinated system for the monitoring of aircraft operational condition and maintenance scheduling.

[4] 'Exceedence report' – an automatically generated ACARS or EICAS report that is triggered by one or more monitored parameters exceeding a pre-defined condition or value.

surfaces. Laboratory fatigue tests performed by the manufacturer on slot specimens that exhibited the peening damage were mostly inconclusive, with the two more heavily 'damaged' specimens showing lives below and above average[5] respectively. In consideration of those results, it should however be noted that the 'feature type' tests were accelerated tests carried out under simulated operational conditions. Low-cycle fatigue tests were also performed on the material from the disk rim, immediately beneath the rim bolt holes. All specimens tested (six in total) demonstrated lives above the average for the disk material. The disk alloy composition and processing was verified as being generally compliant with the design specifications and the disk manufacturing records.

ATSB Technical Analysis report number 19/03 details the examination of the failed disk. A copy of that report is at attachment A and is also available on the ATSB website (http://www.atsb.gov.au) or from the bureau on request.

[5] Specimen life was assessed against the Low-cycle Fatigue curve applicable to the failed HPT disk. Results are considered low if they fall beneath the envelope representing three times the standard deviation (3σ) from the average life curve.

2 ANALYSIS

2.1 Engine failure

Failure of the left (number-1) engine from ZK-NBC occurred as a result of the fracture and partial liberation of the first-stage high-pressure turbine disk. The disk fracture produced a gross imbalance within the rotor assembly, fracturing the low-speed (N1) shaft, severing the engine core casing and producing rapid seizure of the rotating assemblies. The imbalance and the subsequent torque reaction as the engine seized induced buckling and distortion of the engine-to-wing pylon structure and the partial separation of the outboard fan cowling. The disk segment liberation and escape of high-pressure combustion gasses produced explosive damage to the core cowling and the external engine components and accessories. Although some components, wiring and insulation showed burning and charring from the core rupture, there was no evidence of sustained fire within the engine nacelle and the flight crew received no fire warnings or indications.

2.2 Aircraft damage

An analysis of the trajectory taken by the liberated disk section showed it to have exited the engine core almost vertically, travelling up the outboard side of the pylon and impacting the leading edge flap structure. The resultant damage included heavy gouging of the pylon fairings and the destruction of a 600 mm length of the leading edge flap profile above the engine nacelle[6]. Impact damage from the uncontained failure was otherwise confined to minor impacts on the number-2 trailing edge flap canoe fairing.

The damage sustained by the aircraft as a result of the engine failure did not produce immediate aircraft operational problems. The localised damage to the left wing leading edge profile was not sufficient to produce asymmetric handling characteristics and the impact had not damaged the leading edge flap actuation mechanisms. The flight crew's identification of the flap damage and subsequent choice of actions considering the potential effects of the damage on the aircraft's performance minimised the risk of controllability problems arising when the flaps were extended for landing. While the potential existed for more significant airframe damage should the disk section have impacted on the inboard wing or fuselage, the design certification of the aircraft type implied that the hazards to the aeroplane had been minimised in the event of such a failure. Federal Aviation Regulation (FAR) Part 25 (transport category aeroplanes), section 25.903(d) (1) refers. Additionally, certification to FAR section 25.571(e) implied that the aircraft design should have been tolerant of likely structural damage sustained from the uncontained failure of high energy rotating machinery.

2.3 Disk failure

Fracture of the first-stage high-pressure turbine disk resulted from the initiation and growth of a low-cycle fatigue crack at the base of a turbine blade fir-tree slot. The

[6] As a result of the flap and engine pylon damage, the engine failure event was classified as an accident in accordance with the definition published in Annex 13 to the International Convention on Civil Aviation (Ninth Edition).

primary crack, and two other secondary cracks identified during the investigation had initiated from the transition point between the rear disk face slot radius and the slot bottom. Radial crack growth occurred in-service, initially by an intergranular fatigue mechanism, which transitioned to progressive cyclic overload as the cracks advanced. At a radial depth of approximately 39 mm, the critical defect size was reached and the fracture propagated by rapid ductile overload, liberating the disk segment and causing the engine failure. The turbine disk had accumulated 42,069 hours and 12,485 operational cycles at the time of the fracture. It was not possible to determine the period over which the fatigue cracks had been developing.

A review of the complete disk history found no anomalies in respect to maintenance actions, nor was there any evidence of prior operational events that might have compromised the disk life. An upgrade procedure (service bulletin SB72-639) was undertaken when the disk was at approximately two-thirds of its total defined life of 15,000 cycles and associated with that work was the repair and re-shot peening of mechanical damage to a number of unspecified slot edges. The investigation found that the areas of crack formation had sustained appreciable mechanical damage from the shot peening process, producing numerous surface features that could act as fatigue crack initiation sites. While tests conducted on the disk slots by the engine manufacturer did not provide evidence that the peening damaged areas had acted to reduce the fatigue life of the disk material, the physical evidence arising from the examination supports the peening induced surface damage as being a significant factor contributing to the premature fir tree slot fatigue cracking. Damage during the slot machining (broaching) process or incompletely repaired tooling damage also remain as possible factors contributing to the failure, although there was no supporting physical evidence in this regard.

2.4 Disk inspection

The aircraft operator's maintenance records showed that the disk had undergone all relevant inspections prescribed by the engine maintenance manual and applicable service bulletins. A comparison of inspection requirements showed that at the time of the failure, HPT stage-1 disks from CF6-80C2 engines were required to undergo a more rigorous non-destructive inspection of the blade slot bottom regions than was required for the similar CF6-80A disks as fitted to ZK-NBC. That inspection included a more intensive pre-clean, a double surface etch and fluorescent penetrant examination and an eddy-current inspection. The more intensive inspection requirements were implemented as a result of a prior (September 2000) failure of a CF6-80C2 disk that was attributed to slot bottom cracking. That failure had also occurred after a shot-peening repair of the disk slots and rear corners. All corrective actions arising from that failure were specific to the 80C2 series engine only. At the time of the failure of the left engine from ZK-NBC, the additional inspection requirements had not been extended to encompass the worldwide fleet of CF6-80A engines.

2.5 Cabin management

2.5.1 Communications

The investigation found that the flight crew did not follow established operator procedures informing the cabin crew of their intentions to carry out a prepared emergency landing. PA announcements from the flight deck had advised the passengers

and cabin crew to expect a normal landing and the words ‘emergency landing’ were not used when briefing the ISD, or in passenger addresses. Additionally, the flight crew did not follow the standard procedure of using the PA system to call the ISD to the flight deck for an emergency briefing. That action would have indicated to the cabin crew that prepared emergency procedures would be required and allowed the ISD to be properly appraised of the flight crew’s requirements. While a short interphone briefing was given to the ISD by the flight crew, the ISD had not properly heard or understood the intentions of the flight crew and had not read-back, queried or taken any other action to clarify the information given.

2.5.2 Brace for impact

As a result of the inadequate communication, the ‘brace’ instruction from the flight crew was unexpected by most cabin crew and was reported to have alarmed some passengers and confused some cabin crew about the nature of the imminent landing. Instruction and reassurance had not been given to the passengers about the brace call, however the cabin crew reported that most passengers followed their shouted instructions that followed the “brace-brace-brace” call from the flight deck.

The investigation found that some cabin crew reacted correctly to the unexpected ‘brace’ instruction and called ‘Emergency-Grab your ankles’, the terminology associated with unprepared emergency landings. However, some crew who heard the unexpected announcement did not make the emergency call. The intent of the brace instruction before an emergency landing is to have passengers and crew pre-position the body (particularly the head) against the surface it would strike during impact. Having the occupants bend or lean forward over their legs can reduce flailing.

In accordance with company procedures, it is important for all crewmembers to issue brace commands, even when they are uncertain of the precise nature of the situation, to ensure that all passengers throughout the cabin can respond appropriately.

3 CONCLUSIONS

3.1 Significant factors

1. During initial manufacture, a subsequent repair operation, or general handling the first-stage high-pressure turbine disk from the left engine of ZK-NBC had sustained mechanical damage on the rear face and corners of the turbine blade fir-tree slots.

2. During service, fatigue cracking initiated from the rear bottom corner of three of the disk slots.

3. Fracture and the uncontained liberation of a large section from the disk occurred after the growth of one of the cracks to critical size.

4. The left engine failed from damage sustained during the disk failure event.

5. The aircraft sustained control surface damage resulting from impact with debris liberated from the left engine.

6. The flight crew did not follow established procedures in ensuring the cabin crew and passengers were aware of their intention to conduct a prepared emergency landing and did not ensure the ISD fully understood the information that was provided.

7. The ISD did not ensure that he fully understood the information provided by the flight crew, and as a result, did not communicate the flight crew's intentions to the other cabin crewmembers and did not brief the passengers.

8. The 'brace' call given by the flight crew immediately before landing was unexpected and caused alarm among some passengers.

4 SAFETY ACTION

4.1 Local safety action

4.1.1 Disk failure

The failure of high-pressure turbine disk serial number MPOP8478 was the first to have originated from a blade slot initiated fatigue crack in a disk from a CF6-80A engine, although a similar disk failure occurred in a disk from a CF6-80C2 engine in September 2000.

4.1.1.1 Engine Manufacturer

In response to the ZK-NBC disk failure, the engine manufacturer issued service bulletins (SB) CF6-80A S/B 72-0788 and CF6-80C2 S/B 72-1089. Those bulletins were issued to provide for the rework of the stage-1 disk slot bottom corner radii from both the 80A and 80C2 engines, to machine the shot-peen damaged material from the disk rear slot bottom corner and make the geometry less susceptible to future damage. The engine manufacturer also modified the shot peening procedures to more closely control the peening intensity achieved around the slot corner region.

4.1.1.2 United States Federal Aviation Administration

Effective January 28, 2003, the US FAA issued Airworthiness Directive AD 2003-01-05. That directive mandated the requirements of the CF6-80A S/B 72-0779 service bulletin and required the periodic inspection of the applicable disks at each piece-part exposure, or at the next workshop visit for those disks that had not previously been inspected to the 72-0779 service bulletin. Effective March 12, 2004, that directive was superseded by AD 2004-04-07 which retained the initial inspection requirements and required the reworking of certain disks before further flight. In addition, the directive expanded the population of affected engines and removed certain CF6-80E1 disks from service.

4.1.1.3 Australian Civil Aviation Safety Authority

Effective 20 March 2003, the Australian Civil Aviation Safety Authority (CASA) issued Airworthiness Directive AD/CF6/50, which also mandated the CF6-80A S/B 72-0779 service bulletin and was based on the FAA AD 2003-01-05. To mirror the requirements of the subsequent FAA AD 2004-04-07, CASA has released AD/CF6/54 which became effective on 8 July 2004.

4.1.2 Aircraft operator

Following the engine failure, the aircraft operator conducted its own internal investigation of the occurrence and reviewed the actions of the flight and cabin crew against the operator's published operating and emergency procedures. From that investigation, the operator made a number of findings, each of which was addressed by one or more recommendations for corrective action. A summary of those recommendations follows.

1. Flight crew to ISD emergency briefs are to be preferably delivered in person, to specifically state the cabin preparation required and should begin with the statement "This is an emergency brief"

2. Procedures should require the read-back of essential information given during an emergency situation.

3. Flight crews should be reminded of present cockpit voice recorder time limitations and the company SOP requirement to remove power from the CVR as soon as possible after a serious incident (SOP 3.1.8).

4. The aircraft parking / shutdown checklist for each aircraft type should include the item "CVR – remove power (if required)"

5. The aircraft manufacturer is to be consulted regarding the inclusion of specific flap configuration information within the QRH.

6. CRM and Emergency Procedures training should include lessons learned during previous incidents.

7. The Standard Emergency Procedures for an emergency landing should be reviewed for their practicability and consistency between flight and cabin crew actions.

8. Consider the need for a separate command and associated abbreviated procedure for cabin preparation where available time is limited.

9. The adequacy and accuracy of passenger safety information for the 'Brace' position should be reviewed.

5 APPENDIX

5.1 Flight recorder data

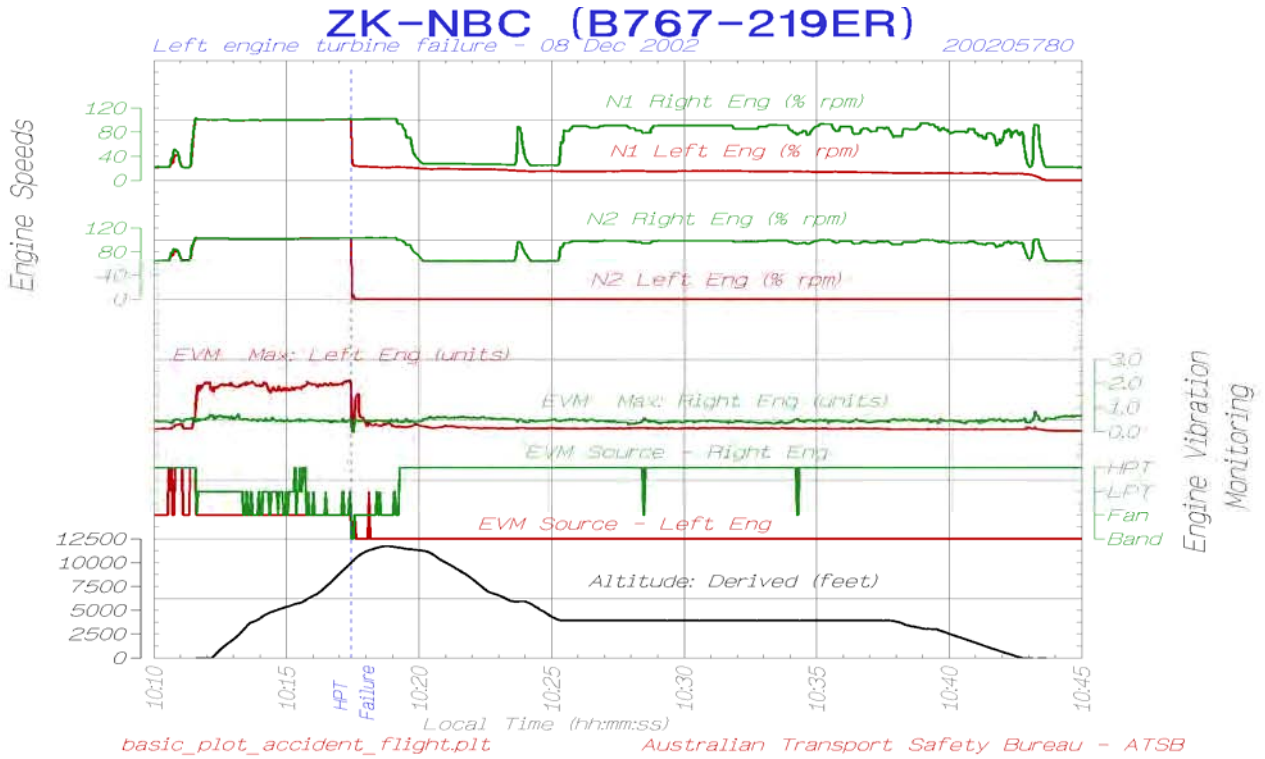

Fig. 1 **basic_plot_accident_flight** – entire accident flight showing recorded values of derived altitude, engine speeds N1 and N2 and engine vibration monitoring maximum levels and source.

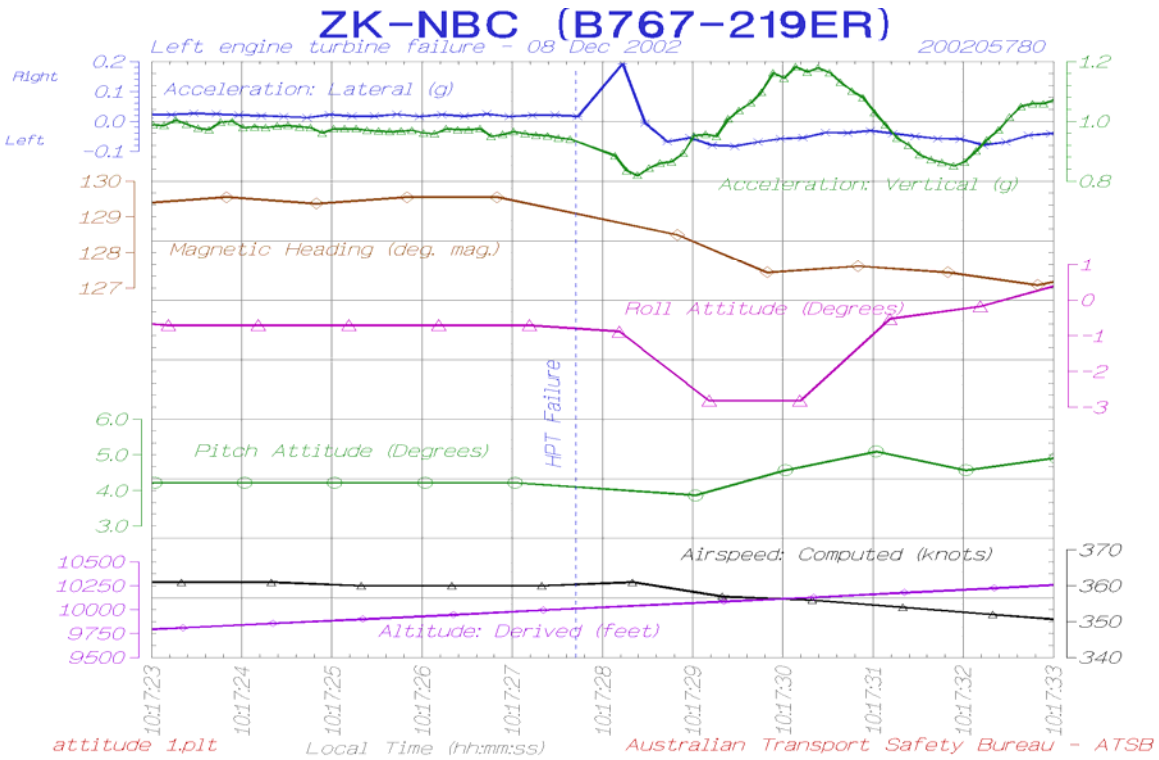

Fig. 2 **attitude1** – ten second period leading up to and after engine failure of the recorded values of derived altitude, computed airspeed, pitch attitude, roll attitude, magnetic heading, vertical acceleration and lateral acceleration.

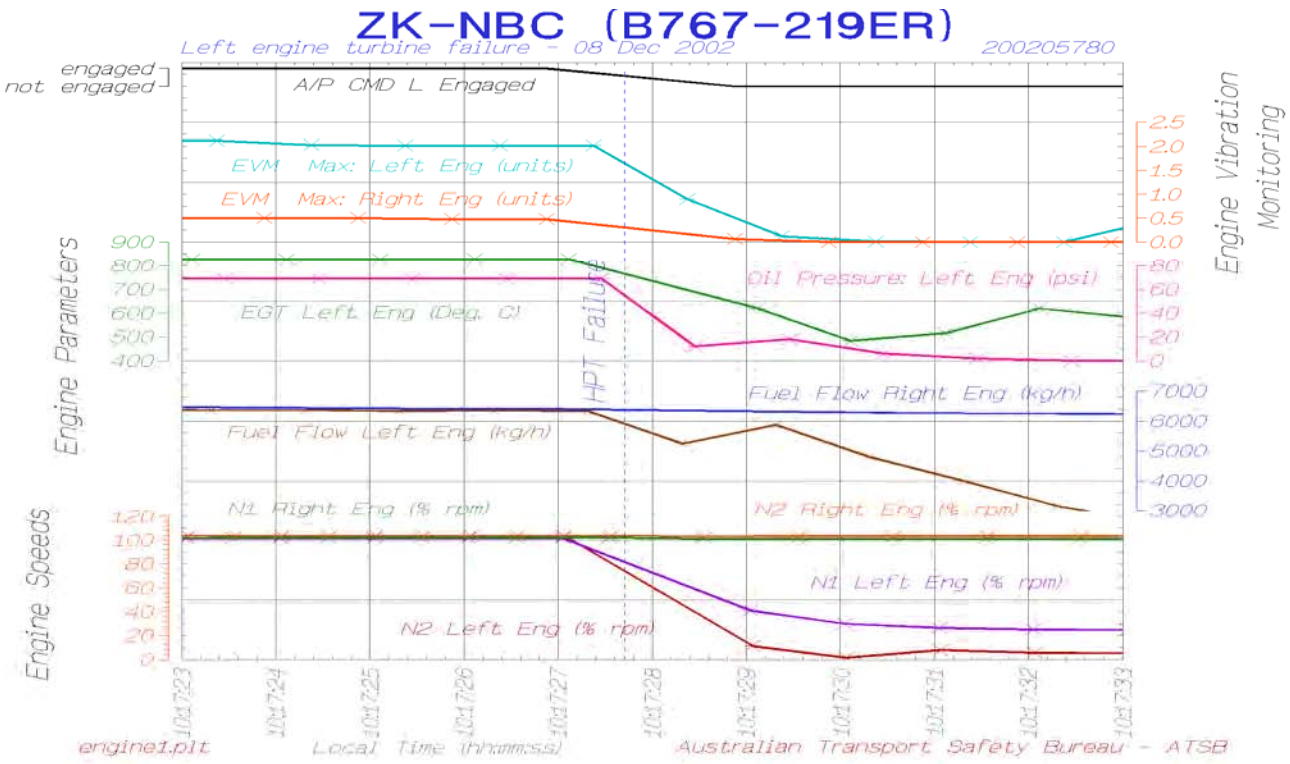

Fig. 3 **engine1** – ten second period leading up to and after engine failure of the recorded values of engine speeds N1 and N2, engine vibration monitoring maximum levels and source, engine fuel flows, left engine EGT, left engine oil pressure and A/P Command – Left discrete.

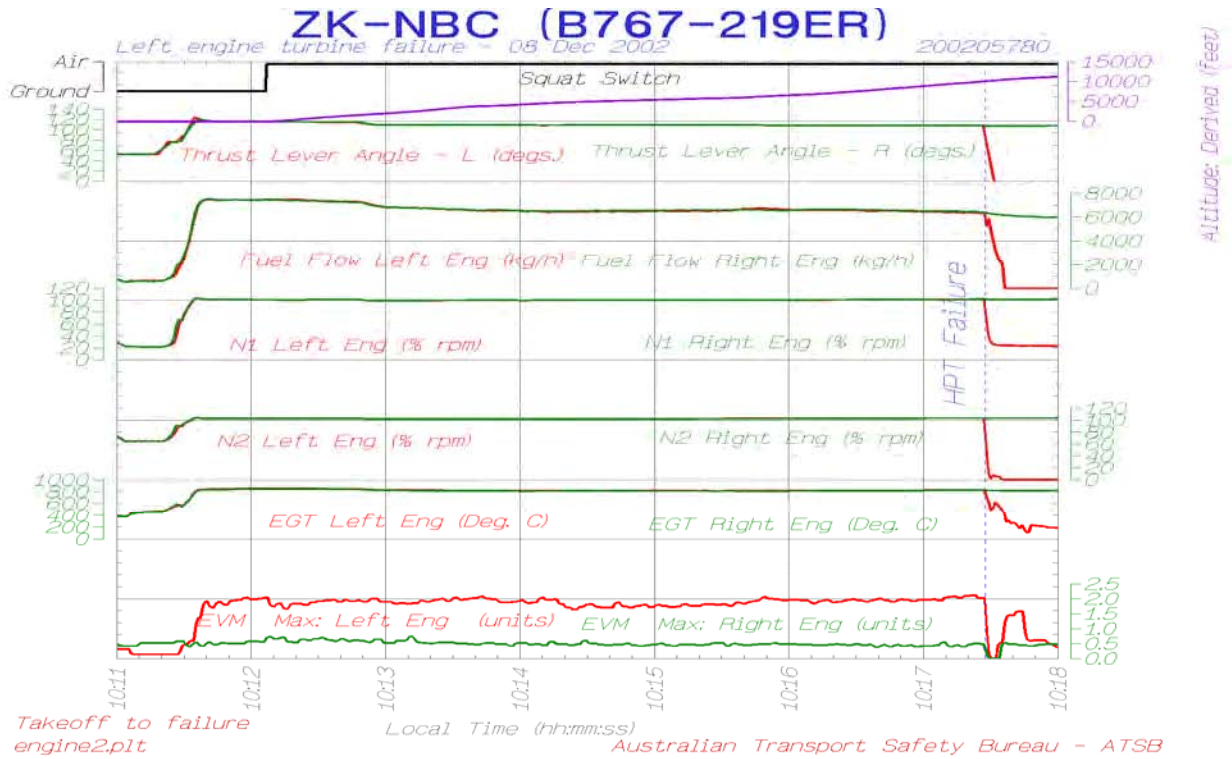

Fig. 4 **engine2** – period from take-off to shortly after engine failure of the recorded values of derived altitude, squat switch, engine speeds N1 and N2, engine vibration monitoring maximum levels, engine fuel flows, EGTs and thrust lever angles

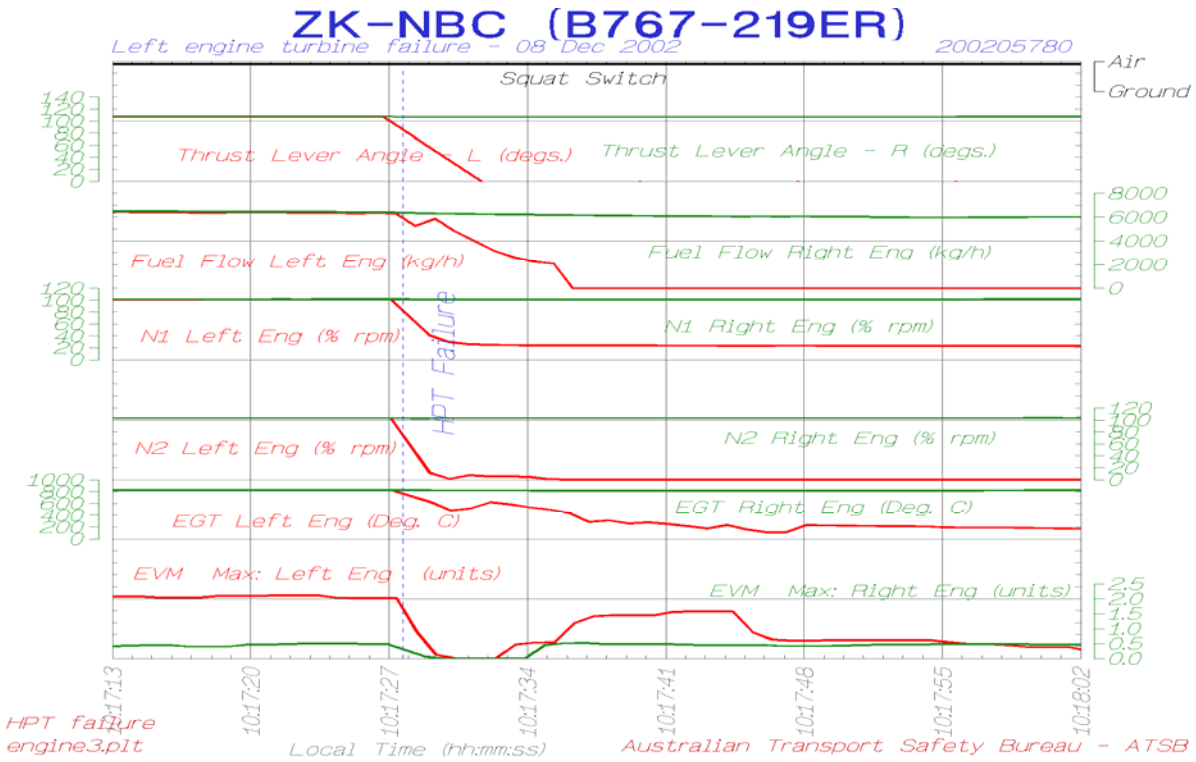

Fig. 5 **engine3** – fifty-second period from shortly before engine failure of the recorded values of squat switch, engine speeds N1 and N2, engine vibration monitoring maximum levels, engine fuel flows, EGTs and thrust lever angles.

ATTACHMENT A – Technical Analysis Report

Report No. 19/03

Task File No. BE/200300016

Occurrence File No. BO/200205780

Examination and analysis of a failed high-pressure turbine disk (General-Electric CF6-80A turbofan engine)

Boeing 767-219ER, ZK-NBC

8 December 2002

1 FACTUAL INFORMATION

1.1 History of the flight

On the morning of Sunday December 8, 2002, Boeing 767-219ER aircraft, registered ZK-NBC, sustained a failure of the number-1 (left) engine during a scheduled regular passenger transport flight from Brisbane to Auckland. The flight crew reported a loud 'bang' and felt the aircraft move to the right, followed by a progressive yaw to the left. After checking instrumentation to confirm the failure, the crew shut down the left engine and completed checklist items before returning the aircraft to Brisbane.

An initial engineering evaluation of the left engine revealed the loss of the outboard fan cowl section and a large rupture of the outboard core cowl, with associated damage to the engine strut and wing leading edge flap above that area (figure 1). The engine core showed the complete circumferential disruption of the high-pressure turbine casing and the loss of a large segment of the first-stage high-pressure turbine disk. The low speed (N1) spool shaft had fractured between the first and second-stage turbine disks.

Fig. 1 Failed left (No.1) engine from Boeing 767-219 ZK-NBC.

1.2 Engine history

The General Electric CF6-80A high bypass ratio turbofan engine (serial number 580-110) had accrued a total of 35,136 operating hours and 11,187 cycles since manufacture. The last full engine overhaul was completed in August 1998, at a life of 21,196 hours / 6,287 cycles. Due to excessive vibration from the high-speed (N2) engine spool, the last workshop visit for the engine was an unscheduled inspection and repair in August 2001, where engine maintenance units 31, 32, 34 from the high-pressure compressor module and the low-pressure turbine module were exchanged.

In summary, at the time of failure, engine serial number 580-110 had accumulated:

Time / Cycles since new:	35,136 hours / 11,187 cycles
Time / Cycles since last overhaul:	13,940 hours / 4,900 cycles
Time / Cycles since last repair:	2,086 hours / 772 cycles.

1.3 Disk operational history

The failed high-pressure turbine disk (part number 9362M58/G07), serial number MPOP8478) was manufactured in September 1984 from an Inconel 718 nickel base alloy (GE specification No. C50TF37, issue S8). Table 1 summarises the documented service history of the disk from manufacture to the time of failure. When first entering service, the engine manufacturer's configuration listing identified the disk as part number 9234M67G24. During the first overhaul of the disk however, it was discovered that the disk carried the physical part number 9362M58G02. During overhaul in 1998, the part number was amended to 9362M58G07, reflecting the application of a Triballoy 400 wear-resistant coating to the 4R and 5R bearing journals (Service Bulletin 72-639).

When first manufactured in 1984, the 9362M58G02 disk had a published life limit of 6,430 cycles. In January 1988, the US Federal Aviation Administration (FAA) approved the first life limit extension to 13,900 cycles and subsequently to 15,000 cycles in February 1992.

	Date	ESN	TSN	CSN	Notes
New	Jun-85	580-273	0	0	
Removed	Feb-88	580-273	1,124	351	Engine not disassembled
Installed	Jun-88	580-273	1,124	351	
Removed	Aug-88	580-273	1,819	566	Engine boroscoped & re-certified
Installed	Sep-88	580-313	1,819	566	
Removed	Aug-90	580-313	8,779	2,927	High N2 vib, first disk O/H, SB72-536 repairs 006, 010 done
Installed	Oct-90	580-305	8,779	2,927	
Removed	Mar-93	580-305	19,370	5,438	Engine removed due HPT blade damage
Installed	Jun-93	580-313	19,370	5,438	
Removed	May-94	580-313	23,235	6,344	HPT NGV damage
Installed	Nov-94	580-110	23,235	6,344	
Removed	Jan-95	580-110	23,669	6,446	Surging, no HPT work done
Installed	Mar-95	580-110	23,669	6,446	
Removed	Feb-96	580-110	28,129	7,585	High cruise EGT
Installed	Nov-96	580-110	28,129	7,585	
Removed	Feb-97	580-110	28,677	7,906	Aircraft end-of-lease.
Installed	Mar-97	580-110	28,677	7,906	
Removed	Aug-98	580-110	34,231	9,692	Time expired HPT vane ring. SB72-676 & 72-639 done at GE
Installed	Apr-99	580-110	34,231	9,692	
Removed	Jun-00	580-110	37,501	10,849	Vibration. HPT blades removed, disk inspected in-situ
Installed	Nov-00	580-110	37,501	10817?	
Removed	Jan-01	580-110	38,229	11,065	No HPT work done
Installed	Mar-01	580-110	38,229	11,065	
Removed	Aug-01	580-110	39,983	11,713	N2 Vibration, HPT module disassembled, disk inspected in-situ
Installed	Mar-02	580-110	39,983	11,713	
Failed	Dec-02	580-110	42,069	12,485	HPT disk failure

ESN – Engine Serial Number
TSN – Time since new (hours)
CSN – Cycles since new

1.4 Disk repair, overhaul and inspection history

The first repair involving piece-part exposure of the first-stage high-pressure turbine disk was completed in 1990, after the engine was removed for high N2 vibration. At that time, the disk had operated for 8,779 hours and 2,927 cycles. Repairs 006 and 010 to engine maintenance manual 72-53-02 were carried out and involved the refurbishment of the shaft section journal chrome plating and the resurfacing of the forward shaft end. Service bulletin 72-536, requiring the replacement of the disk hook

bolts was also completed. The examination of the disk involved a complete fluorescent penetrant inspection, including the firtree slot bottoms. At the time of the inspection, the engine maintenance manual did not require an eddy-current inspection of the slot bottoms.

In March 1993, the disk was overhauled, with a repeat of repairs 006 and 010 and an eddy-current inspection of the disk rim bolt holes and bore to service bulletins' 72-604 and 72-607.

In February 1996, the disk was removed at 28,129 hours TSN, 7,585 CSN. The disk was chemically cleaned and a dimensional inspection and eddy-current inspection of the rim bolt holes completed.

In August 1998, the disk was removed and sent to the manufacturer for an upgrade to part number 9362M58G07 (application of the triballoy bearing journal coating, SB72-639). Associated with this work was a comprehensive inspection process involving fluorescent penetrant inspection and visual examination. The manufacturer's inspection records for this work indicated that fir tree slot edge nicks and other surface damage was found on the rear face of the disk at that time, however the records did not identify the specific blade slot/s that were affected. The damaged areas were repaired by blending in accordance with the engine maintenance manual (repair 012), with penetrant inspection and shot-peening following. Shot-peening records showed that the process had been applied to the disk bore and bore-edge radii, rear embossments, rear slot edges and the shaft internal journal surfaces. The engine manual specifications for the repair 012 shot peening process required 125% coverage at an Almen intensity of 0.004 – 0.008A, using S-110 cast steel shot. The manufacturer indicated that the shot peen vendor had used S-170 shot instead of the required S-110, however the required Almen intensity had been achieved.

The disk was re-installed in engine 580-110 and returned to service in April 1999. In June 2000, the disk was de-bladed and visually inspected in-situ, with another similar unscheduled inspection following in August 2001.

At the time of failure, the disk had accumulated 7,838 hours / 2,793 cycles since the last overhaul (August 1998) and 2,086 hours / 772 cycles since the last workshop visit (August 2001).

1.5 Disk failure

A preliminary examination of the engine after removal of the turbine fairings revealed extensive mechanical damage to the casing, ductwork and wiring around the plane of the first-stage high-pressure turbine rotor (figure 2). The damage had effectively severed the engine at that point, with the fracture of the low-speed (N1) shaft allowing the casing sections to move apart by approximately twenty mm (figure 3). Inside the severed casing, the HPT1 rotor showed extensive damage, with all blades either lost from the disk or fractured at the base of the airfoil section (figure 4). The disk itself had lost a large, crescent-shaped section from the outer rim and web, encompassing approximately fourteen blade slots (figure 5). A characteristic localised area of discoloured fracture surface was noted at the base of the blade slot on the trailing end of the fracture (figure 6). The liberated disk section was not recovered from the internal remnants and was presumed lost from the engine during the initial failure event.

Fig. 2 Core damage to the engine around the plane of the first-stage high-pressure turbine disk.

Fig. 3 Separation of the engine core (arrowed).

Fig. 4 View of the stage-1 HPT disk through the severed case. Many blades fractured or lost from the disk.

Fig. 5 Rear face of the stage-1 HPT disk, showing the loss of the rim and web section.

Fig. 6 Primary disk fracture showing an area of discoloured prior cracking at the base of a blade firtree slot.

To allow laboratory metallurgical evaluation of the disk failure, the HPT-1 rotor was removed from the engine and the adjoining high-speed shaft components by thermally sectioning the disk shaft through the large air holes forward of the disk hub. After appropriately protecting the fracture surfaces, the disk was sent to the ATSB Technical Analysis laboratories in Canberra.

1.5.1 Identification markings

The main disk identification marks were located along the top edge of the blade posts and were either hard-stamped or engraved. The markings identified on the failed disk when examined in the laboratory were as follows:

07482	*Coding indicating GEAE manufacture*
9362M58G0XXX 7	*Part number (X represents overstamped lettering)*
S/N MPOP 8478	*Serial number*
72-676R2	*Application of SB72-676 rev 2 (disk radius inspection)*
26352	*Disk original diameter 26.352 inches (across posts)*

The disk also carried the numerals '1' and '5' respectively on the rear face of two blade posts each – these representing the datum marks for the identification and numbering of the disk fir tree slots. The slots were numbered sequentially in the clockwise direction as viewed from the rear looking forward. The disk contained a total of 80 firtree slots.

1.5.2 Fracture surfaces

On the basis of the fir tree slot markings, the disk failure had occurred between slots 46 and 60, with the principal fracture origin associated with the discoloured area located at the base of slot 60 (figure 7). Further visual examination identified two other blade slots that were also cracked. Slot 72 presented a full width crack that extended radially along the rear disk face (between the bolt-hole embossments) for approximately twenty-five mm (figure 8). The same crack also ran radially along the forward disk face for around ten mm before turning tangentially and intersecting the rim bolt hole between slots 72 and 73. A smaller slot bottom crack was also found at the base of slot 64 – that feature extended eight mm radially and fourteen mm axially from the rear corner (break-edge) of the blade slot.

To facilitate the fracture surface analysis, electric discharge machining (EDM, wire-cutting) was used to excise samples containing the primary fracture origin at slot 60 and the secondary cracking visible in fir tree slot 72 (figure 9). The cutting was performed through the centreline of the disk posts to preserve the integrity of the adjacent fir tree slots for later evaluation.

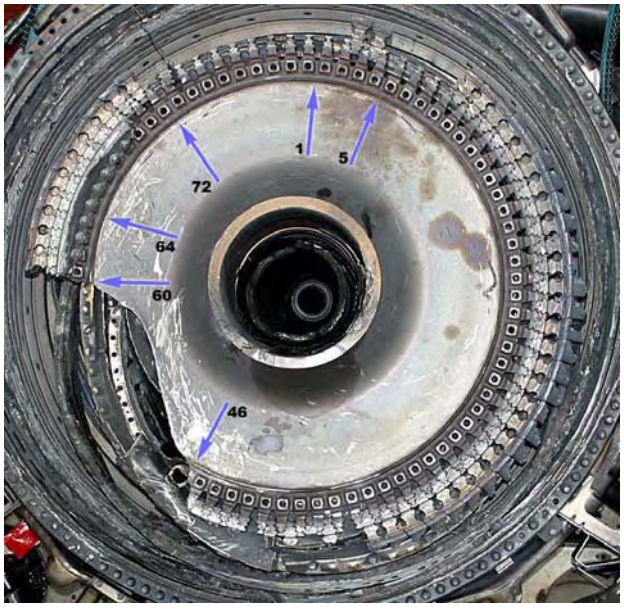

Fig. 7 View of the rear face of the stage-1 HPT disk showing the slot numbering. The primary fracture extended between slots 46 and 60, with additional cracking found at slots 64 and 72.

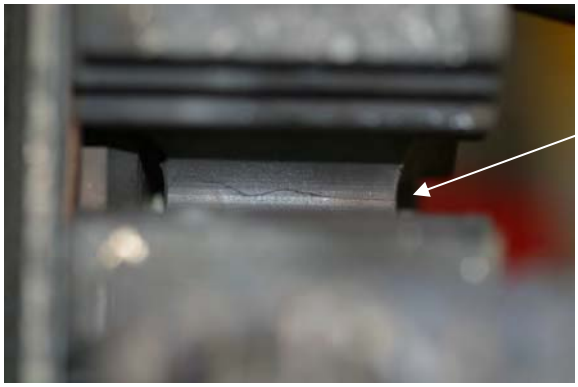

Fig. 8 Visible cracking found at the base of firtree slot 72.

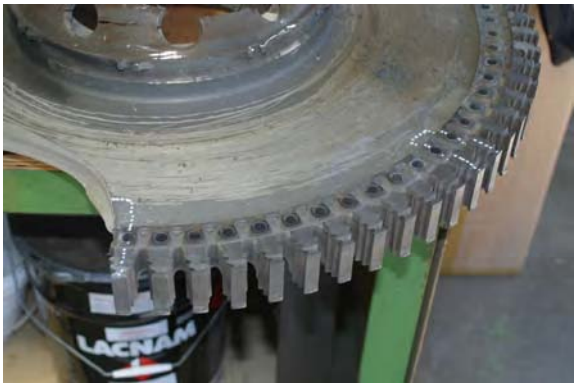

Fig. 9 Disk slots as marked out for EDM of samples for laboratory examination.

Slot 60 cracking

After removal of the slot 60 sample, it was evident that the primary cracking had diverged into the rim bolt hole (as observed in slot 72), forming a triangular shaped area extending from the break-edge corner to the base of the embossment and ten mm along the slot base. Secondary radial cracking had initiated from near the base of the embossment region, resulting in the formation of two separable sections (figures 10, 11).

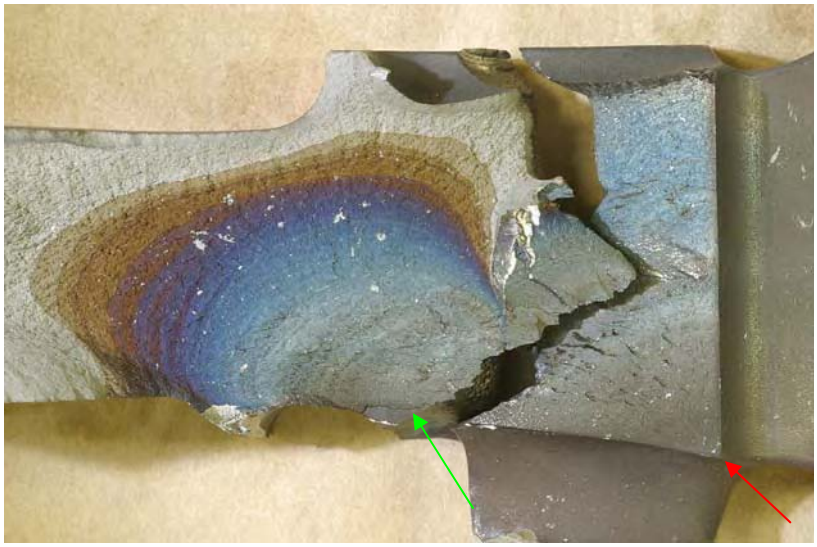

Fig. 10 Specimen removed from the disk encompassing the primary fracture initiation region. Fractographic analysis showed primary fatigue crack initiation from the rear slot corner (red arrow), with secondary cracking initiating from the plane of primary cracking towards the base of the rear embossment (green arrow).

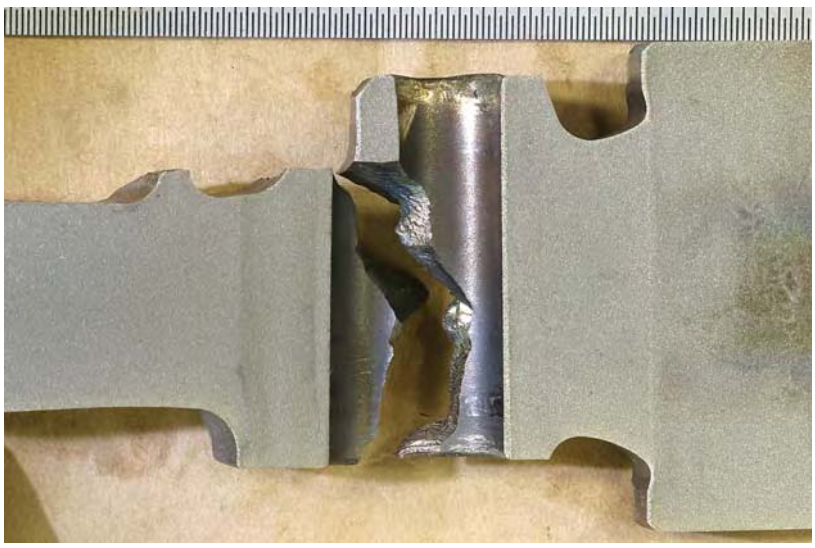

Fig. 11 Wire-cut surfaces of the specimen above, showing the divergence of the primary fatigue cracking into the rim bolt hole.

Examination of the primary fracture at low magnification located the origin at the tangency point between the rear break-edge and the base surface of slot 60 (figure 12). Little further detail was available at higher magnification (figure 13), with no evidence of mechanical damage, indentations or other anomalous features observed on the surfaces surrounding the fracture origin. The early fracture surface features suggested the propagation of cracking by intergranular fatigue. The conchoidal, radiating pattern and associated lightening of the oxide colouration shown by the secondary cracking was indicative of a propagating fracture, with the surface morphology consistent with cyclic tensile overload. The clear, widening steps in the oxide patina towards the outer limits of the progressive fracture indicating accelerated crack growth as the defect became larger. The point of final fracture and disk failure was defined at the boundary of the outermost oxidised area (figure 14), where the fracture had adopted a clear morphology of ductile tensile overload. At this point, the fracture had propagated for approximately 39 mm below the firtree slot base and extended longitudinally for almost the full disk thickness in that area.

Fig. 12 Closer view of the primary fracture origin. Note the absence of characteristic fatigue propagation marks, attributed to crack growth by an intergranular propagation mode.

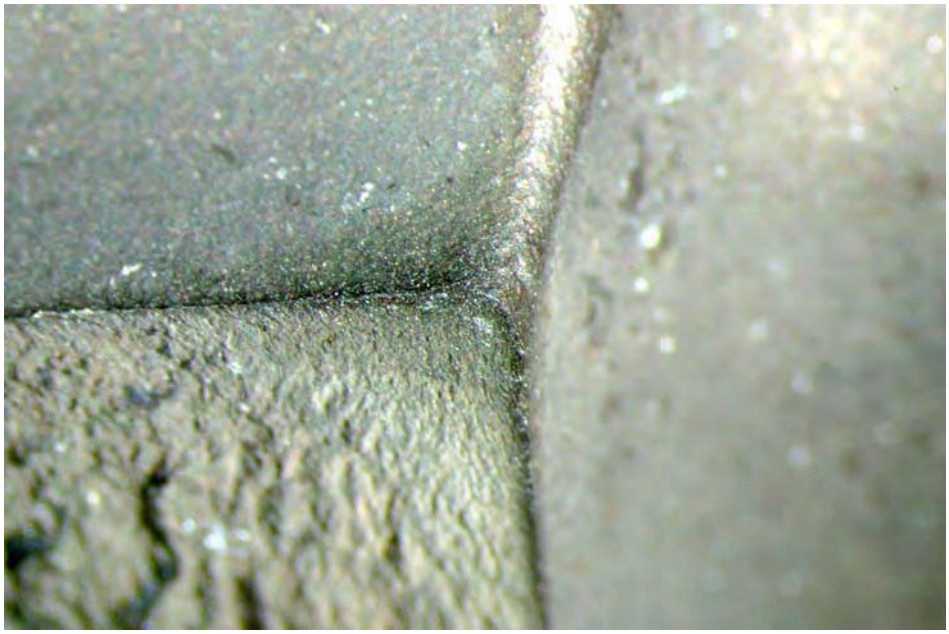

Fig. 13 Low-power microscopic view of the crack origin. The surrounding slot, corner and rear faces appeared free of damage at that magnification.

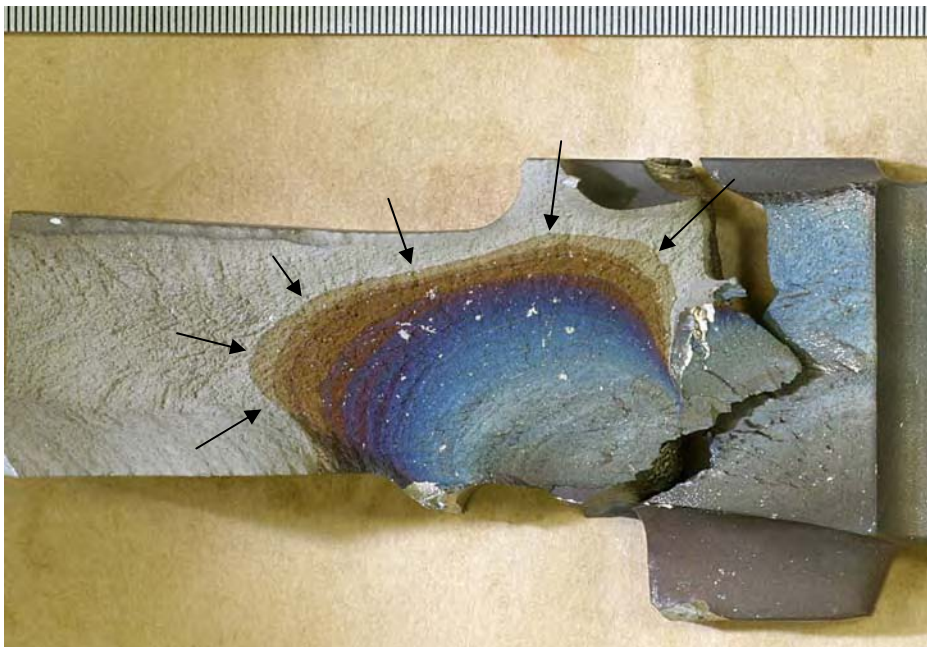

Fig. 14 General view of the primary fracture showing the limit of progressive crack growth and the transition to final ductile overload failure.

Slot 72 cracking

Examination of the slot 72 sample before separation of the crack surfaces showed a slight radial offset in the fracture surfaces at the rear end of the slot (figure 15), with the high point located on the leading side of the fir tree slot. Low-power stereomicroscopic examination of the surfaces surrounding the rear break-edge found no evidence of tooling marks, indentations or other physical abnormalities. The rear disk face cracking extended radially to below the lower embossment edge, before turning circumferentially and propagating inboard of the rim bolt hole (figure 16). On the forward disk face, the slot bottom cracking diverged directly into the bolt hole with only a short radial propagation along the forward face (figure 17). The bore of the rim bolt hole (figure 18) showed the near intersection of the forward and rear crack ends, with only a shallow saw cut required to enable separation of the crack surfaces. On examination, the crack origin was located at the rear break-edge corner, with subsequent radial propagation in a manner very similar to the slot 60 cracking (figure 19). Features associated with a fatigue mechanism were identified extending out from the origin and no gross material abnormalities were observed.

Figs. 15 & 16 Rear-face view of the cracking found within firtree slot 72.

Figs. 17 & 18 Forward face and internal bolt hole views of the slot 72 cracking.

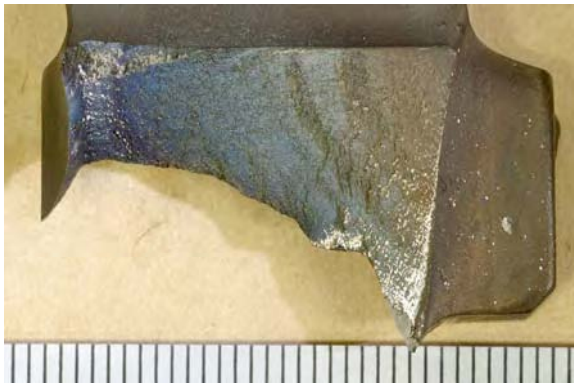

Fig. 19 Separated surface of the slot 72 cracking. Note the close similarities to the primary cracking in slot 60 that caused the disk failure (figure 12).

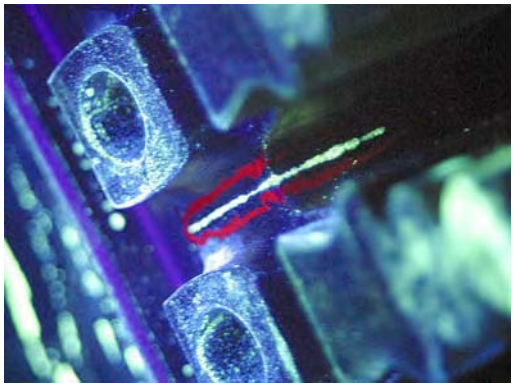

Fig. 20 Fluorescent-penetrant crack indication along the base and rear face of firtree slot 64.

Slot 64 cracking

The suspected presence of cracking within the number-64 fir tree slot was identified during general examination of the disk in the laboratory. Subsequent fluorescent dye-penetrant inspection (figure 20) and eddy-current testing of the disk confirmed the cracking and showed it extending approximately 15 mm along the slot bottom (axially) and around 18 mm along the rear disk face (radially). After the disk was released by the ATSB, the manufacturer carried out further examination of the cracking, the results of which again confirmed a fatigue cracking mechanism with the origin at the rear break-edge slot bottom tangency point[1].

1.5.3 Crack initiation & growth

Stereomicroscopy, scanning electron microscopy (SEM) and optical metallography was carried out on representative areas of the slot 60 and slot 72 primary fatigue crack surfaces to characterise the nature of the crack origin and the local condition of the fir tree slot, break-edge and rear disk face surfaces.

Slot 60

The general slot and rear face surfaces showed a generally uniform, dimpled appearance that was characteristic of the shot-peening process prescribed for initial disk manufacture and post-repair operations (figure 21). The tangency point origin of the slot 60 cracking was associated with a region of flowed material with shallow lap-like features identified as peened surface extrusion folds (PSEF), which extended part-way

around the break-edge profile (figure 22). The fracture surface morphology in proximity to the origin showed uniform general features characteristic of intergranular fatigue cracking (figure 23), however that changed to a mixed mode of intergranular fatigue and ductile overload within the plane of radial cracking located inboard of the rim bolt hole (figure 24). Towards the limit of cyclic, in-service crack growth, the fracture morphology was almost exclusively dimpled ductile overload with an even distribution of large carbides (figure 25).

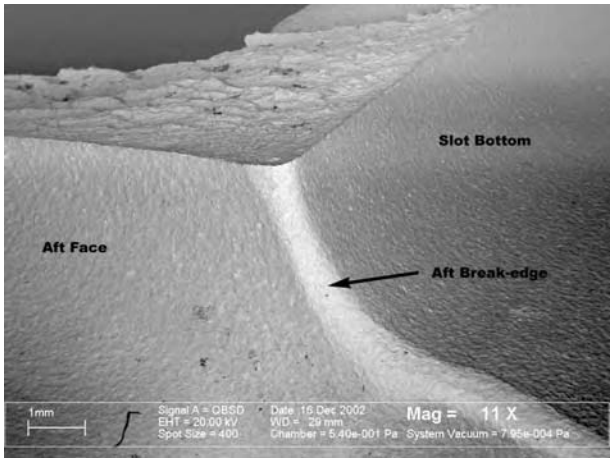

Fig. 21 SEM view of the rear break-edge leading to the crack origin. Dimpled surface typical of shot peening.

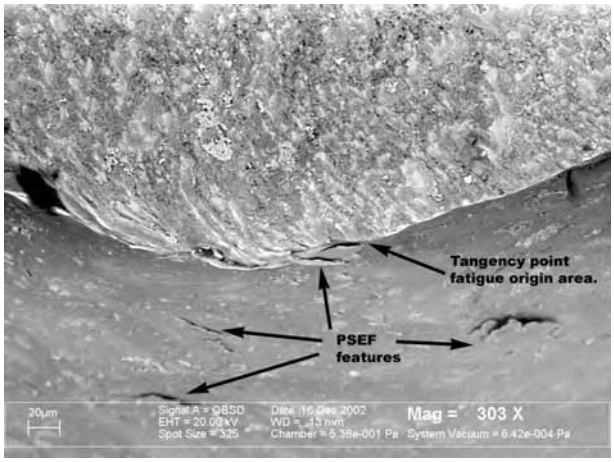

Fig. 22 SEM view of the primary crack origin, showing the presence of PSEF defects on the external surfaces.

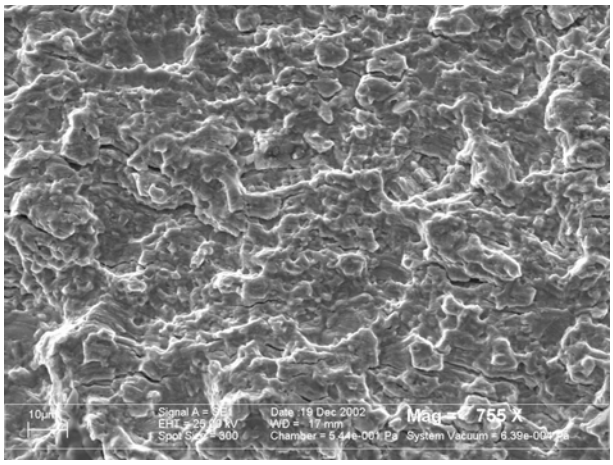

Fig. 23 SEM view of the fracture morphology adjacent to the origin. Typical of intergranular fatigue.

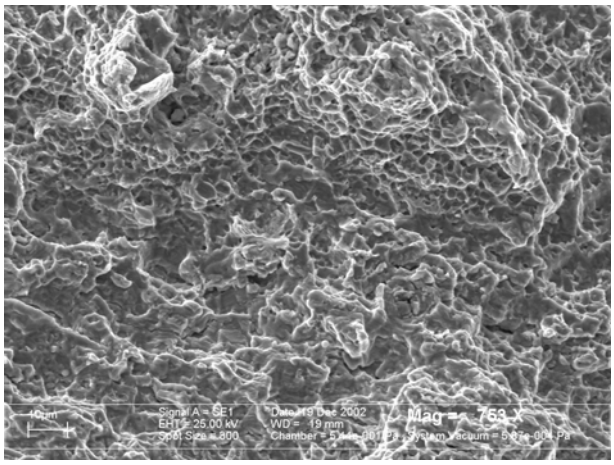

Fig. 24 SEM view of the fracture morphology at the transition from intergranular fatigue to predominantly cyclic ductile overload.

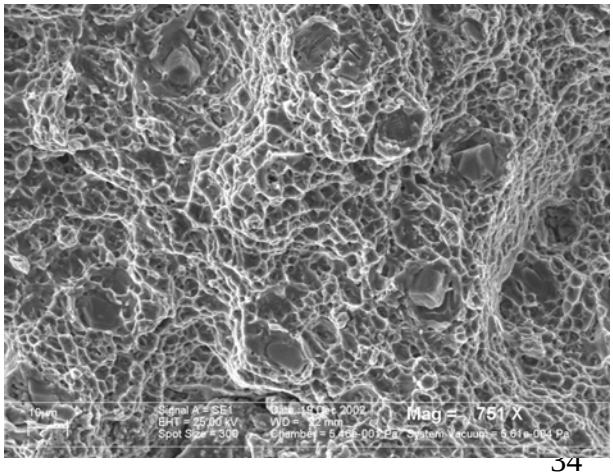

Fig. 25 SEM view of the fracture towards the edge of the area of prior cracking. Essentially 100% dimpled ductile overload.

Metallographic characterisation of the fatigue origin area was achieved by controlled polishing into the fracture surface, producing a radial plane through the rear break-edge profile. Examination in the unetched condition (figures 26 and 27) showed a series of shallow (25μm maximum depth) lap-like features around the break-edge and along the rear disk face. The features were characteristic of the various PSEF features observed under the SEM. When etched with 'Tuckers' reagent, a 20-25 μm deep surface zone of heavily deformed transformed martensite was evident around the break-edge and rear face surfaces (figures 28 and 29), with a prominent direction of flow around the break-edge toward the slot. The surface material within the slot itself showed little evidence of the deformed grain structure, with the transition to the deformed break-edge material being very abrupt. The general microstructure of the disk alloy was very fine, equiaxed austenite grains with a distribution of coarse carbide particles. Smaller cuboidal nitride particles were also evident. The strengthening precipitate phases of gamma-prime (γ′) and gamma-double prime (γ′′) were not resolvable at the magnifications used.

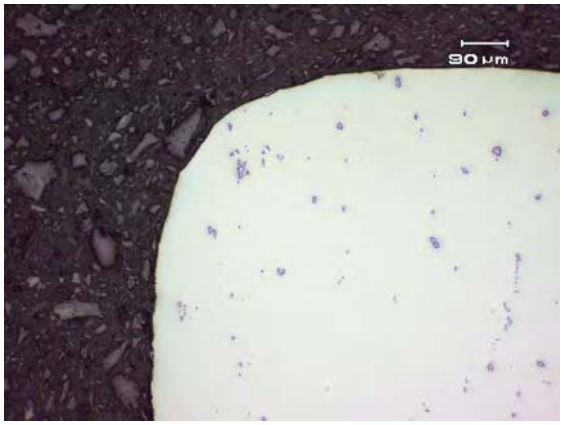

Fig. 26 Unetched metallographic view of the rear break-edge at the fracture origin. Dark particles are coarse carbides.

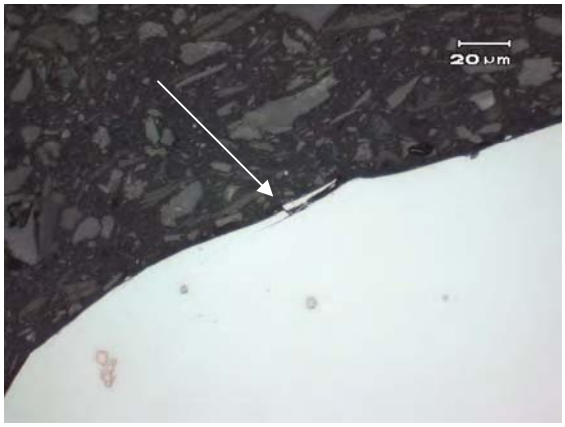

Fig. 27 Higher magnification unetched view showing a shallow surface fissure associated with a PSEF defect.

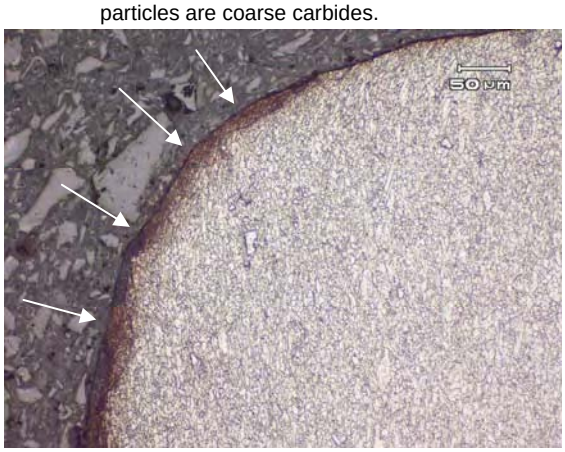

Fig. 28 Etched view of the section shown in fig. 26 showing a heavily deformed surface layer around the break-edge. Slot base is at top.

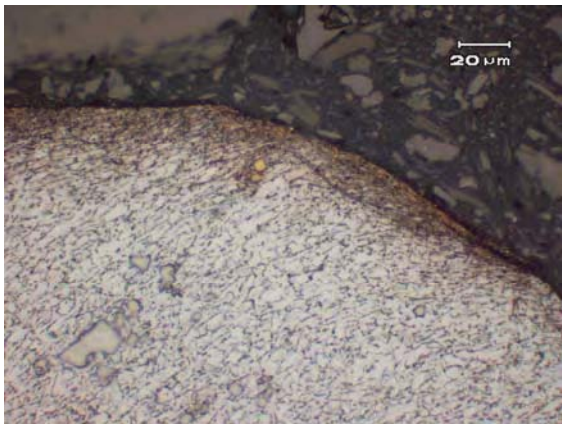

Fig. 29 Higher magnification view of the etched break-edge, showing another lap-like feature associated with the shot peening.

Slot 72

The rear disk face and fir tree surfaces of slot 72 showed a similar appearance to slot 60, with the dimpled effects of shot-peening clearly evident (figure 30). The slot bottom and rear face surfaces showed notable differences in the extent of deformation produced by the peening operation. Figure 31 shows a marked transition from the heavy peened surfaces of the rear face and break-edge to the visibly lighter peened slot bottom

surface. Significant PSEF features were prevalent around the break-edge profile and particularly prominent along a ridge of material at the break-edge-to-slot tangency point (figure 32). No localised indentations or other mechanical damage was found on the examined surfaces. Although deformed by mutual contact during crack growth, the fracture surfaces showed sufficient detail to again identify the origin at the rear break-edge tangency region (figure 33) and also showed the microstructural flow associated with the shot peening process. Fracture mode was again intergranular fatigue and was essentially identical to the morphology shown by the primary (slot 60) fracture.

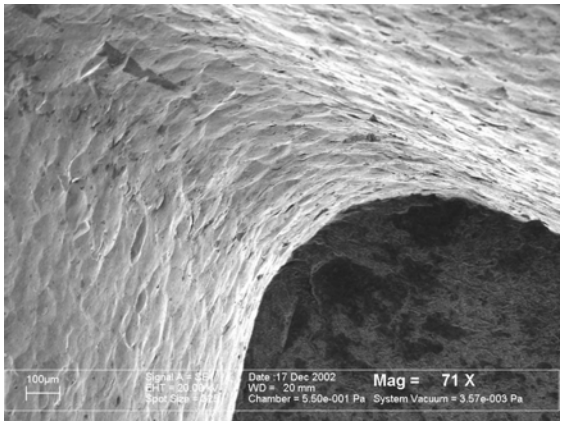

Fig. 30 SEM view of the rear break-edge of slot 72. Dimpled surface typical of shot peening.

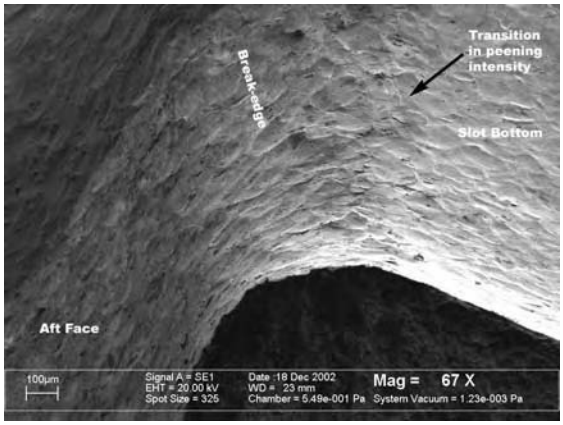

Fig. 31 SEM view of the rear break-edge showing a clear transition in the effects of peening intensity at the slot break-edge tangency point.

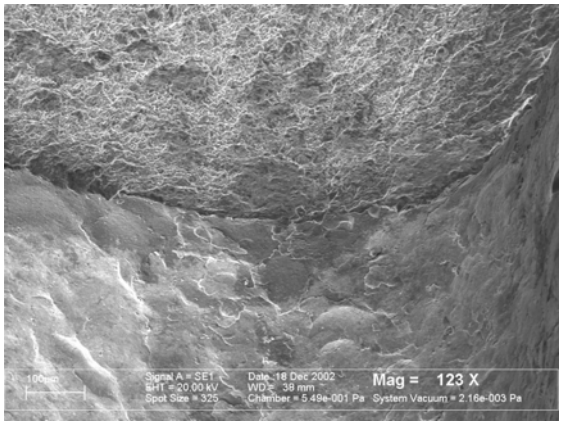

Fig. 32 Slot 72 rear break-edge showing extensive PSEF features.

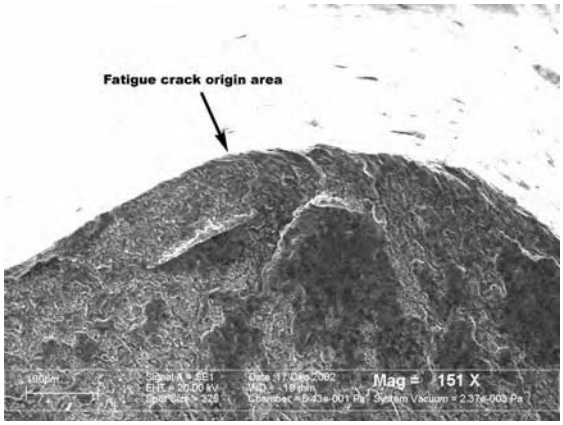

Fig. 33 Crack origin again identified at the rear break-edge tangency point.

Metallography of the rear break-edge region showed the surface deformation associated with the peening, which again showed a very abrupt transition into the fir tree slot (figure 34). Associated with this transition was a ridge of flowed material that had been raised above the surface by the effects of the shot peening (figure 35). Features such as those are consistent with lower shot incidence angles during peening, where the repeated angular impacts produce a directional shear force within the surface material. The general material microstructure was typical of the disk alloy and consistent with the structures observed in the slot 60 specimen.

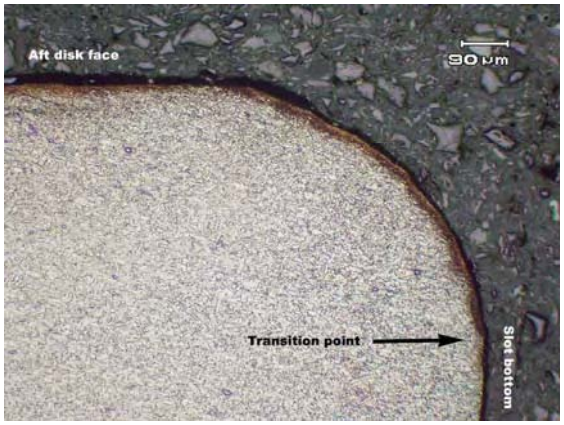

Fig. 34 Etched metallographic view of the slot 72 break-edge profile, showing the abrupt end of the deformed layer at the slot tangency point.

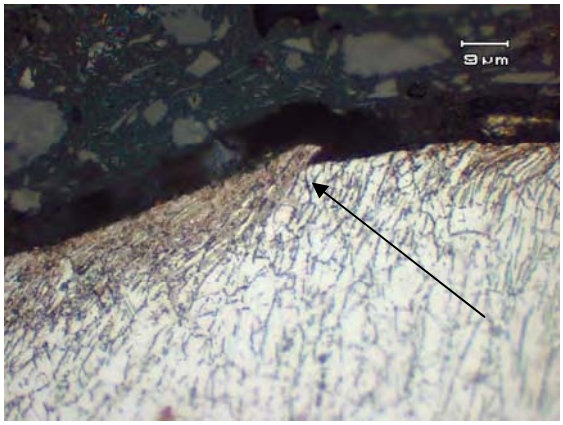

Fig. 35 High magnification view of the end of the heavily deformed layer shown in figure 34. Note the sharp raised ridge of flowed surface metal.

1.5.4 Material and properties

The engine manufacturer's specification for the stage-1 high-pressure turbine disk material (C50TF37-S8) nominated the production of the disk as a forging from a precipitation-hardening nickel based alloy meeting the general chemistry requirements for an Inconel alloy 718 alloy (UNS N07718).

Spectrographic analysis of a disk sample was conducted by Spectrometer Services Pty Ltd, Coburg Victoria, returning the following results.

Fe	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	V	Nb	Ti	Al	Co
17.9	.03	.10	<.1	<.005	<.01	~Bal	18.0	3.0	.10	.03	5.9	.96	.49	.32

~ Bal = approximate balance of composition.

Allowing for the check-analysis tolerance limits published in AMS 2269, the reported Niobium (Nb) content was 0.2% in excess of the upper limit. It was understood however that the uncertainties relating to the analytical method used for the Niobium determination were higher than normal for the technique, and thus the result could not be considered an unequivocal non-compliance.

Niobium is predominantly present within the alloy to provide for the formation of the principal precipitation-hardening γ'' phase (gamma double prime). Over-ageing or in-service overheating of the 718 alloy can cause the γ'' phase to coarsen or re-solutionise with a corresponding loss in alloy strength and associated mechanical properties. The metallographic examination however showed no evidence of this, nor did it show any indication of the formation of the more stable delta (δ) phase which can be a further indication of overheating.

Conventional Vickers diamond-pyramid hardness tests conducted on both metallographically prepared specimens (slot 60 and 72) returned results within the range of 450 – 478 HV_{10} (423 – 448 HB equivalent when converted in accordance with ASTM E140-02). These values are in compliance with the manufacturer's specification for alloy forgings heat-treated to the specification's 'Class B' requirements. The values

also compare favourably with the test results provided by the material supplier to the engine manufacturer (444 HB).

1.5.5 Further testing and evaluation

Upon completion of the overview examination of the disk failure by the ATSB, the disk was returned to the engine manufacturer's facilities in the US for further investigation of the failure and characterisation of the disk firtree slot cracking. The results of that work were provided to the relevant parties to the accident investigation and are summarised as follows.

Crack evaluation (slot 64)

The fine cracking detected within firtree slot 64 was removed from the disk and examined visually and under the SEM, before being separated in the laboratory to expose the crack surfaces. The fracture morphology and crack origin were found to be very similar in nature and location to the slot 60 and 72 features. A similar heavily deformed surface microstructure was identified along the rear face and break-edge, with the associated random PSEF defects. A series of micro-hardness surveys were conducted on the metallographic section – located beneath the slot and rear face surfaces. The general trend illustrated by the series of tests was a progressive increase in hardness towards the slot corner, although the rear face results generally showed elevated values for the full length of the traverse.

Metallographic examination (slots 12, 21, 23 and 63)

The four fir tree slots noted above were selected for metallographic examination along an axial-radial section through the slot bottoms. All four slots exhibited surface grain deformation and flow along the rear face and around the rear break-edge, consistent with the effects of the shot-peening process. Surface PSEF features of a similar nature to the cracked slots were also observed. All four slots showed a circumferential ridge of metal around the slot bottom tangency point of the rear break-edges. Metallography confirmed this to have formed from the flow and extrusion of the surface structure under the effects of shot peening. None of the slots showed any evidence of fatigue crack initiation.

Residual stress measurements (slots 39, 60, 61 and 72)

Using X-ray diffraction techniques, the residual stress and percent cold-work present in the surface material from each of the nominated slots was measured and tabulated. Five locations were examined in each slot, representing the forward ends, centre and rear ends of the slots and the forward and rear faces of the slots below the respective break-edges. From the test results, the engine manufacturer concluded that the required peening intensity had been achieved, based upon the maximum measured depth of residual compressive stresses. It was noted however, that the measurement data did not provide for the assessment of the level of coverage achieved during peening, nor whether that coverage had been excessive or otherwise.

Low-cycle slot fatigue testing (slots 6, 11, 22, 38, 40, 62 and 70)

'Feature type' (meaning actual disk slot specimens) low-cycle fatigue (LCF) tests were conducted at 538°C (1000°F) on the slots above. Subsequently, slots 66, 68, 74, 76 and 78 were tested at room temperature to clarify the results of the elevated temperature

testing. Selection of the slots for testing was based on obtaining specimens that showed varying levels of the physical ridging of material at the rear end of the slots. Upon evaluation, it was found that the seven elevated temperature specimens failed at a range of lives and from a range of different locations. There was no correlation evident between the extent of the rear slot ridging and the demonstrated fatigue lives, nor was there any particular bias towards crack initiation being associated with the slot ridging or other peening-induced features. Of the range of fatigue lives demonstrated, two of the seven specimens were below the nominally accepted deviation from the standard-life curve, while the remaining five specimens exhibited lives above the average. For the purposes of the LCF testing, the fatigue life consumed during the service life of the disk was not factored into the results.

Of the five specimens subject to room temperature LCF tests, all were observed to initiate fatigue cracking at the slot bottom – rear break-edge tangency point. Upon examination, three of the four specimens that exhibited a circumferential ridge of material raised by the peening process also showed fatigue crack initiation from that area. All five specimens showed LCF lives that were below the average life curve, with standard deviations from the average ranging from –1.47 to –4.46.

Low cycle material fatigue testing

Six tangentially oriented specimens of the disk material from below the rim bolt-holes were removed for rotating-beam low cycle fatigue testing using smooth bar specimens. Two specimens each were removed from locations adjacent to slots 22, 39 and 62, with one of each being tested at alternating stresses of 621 MPa (90 KSI) and 689 MPa (100 KSI) respectively. All test specimens exhibited fatigue lives above the average life curve applicable to the CF6-80A HPT stage-1 disk.

Conclusions

On the basis of the investigatory work conducted at the ATSB laboratories and subsequently in the United States, the engine manufacturer was unable to determine conclusively the root cause of the disk cracking. Probable contributing factors were listed as one or a combination of:

- Damage to the rear end of the fir tree slots induced during manufacture by either the slot broaching or subsequent rear break-edge finishing.
- Handling damage sustained at the rear end of the fir tree slots
- Damage sustained by abusive shot peening of the rear end of the fir tree slots.

1.6 Prior disk failures

Prior to the event in question, there had been three uncontained failures of CF6-80 series high-pressure turbine rotors. The first failure occurred in August 1991 and involved the separation of the stage-1 disk rim from a CF6-80A engine. Investigations attributed that failure to cracking within the rim bolt holes and, as a result, an eddy-current inspection procedure for the bolt holes was added to the engine manuals for both the CF6-80A and 80C2 engines.

The day following that event, a Boeing 767-200 aircraft sustained the failure of one of its CF6-80A engines while in climb, as a result of the complete separation of the stage-1 HPT disk. Metallurgical examination of a recovered section of the disk identified fracture initiation at a localised area of electrical arcing produced during chrome plate repair of the disk shaft section. Corrective actions implemented following the event included disk field inspections and engine manual process changes.

The third failure event involved a CF6-80C2 engine and occurred on 22 September 2000 during an engine maintenance run. The failure again involved the complete separation of the stage-1 HPT disk and produced substantial damage to the Boeing 767-200 aircraft. Investigation found that the primary disk failure originated from fatigue cracking within a disk firtree slot, although the examination was hampered by significant secondary damage to the disk fracture surfaces. The operator's records showed that the failed disk's fir tree slot bottoms had been blend repaired and shot-peened on two separate occasions, the last being 1,675 cycles before the disk failure.

The field inspections resulting from the event required the surface etch and fluorescent penetrant of all CF6-80C2 stage-1 and 2 turbine disks and the eddy-current inspection of the slot bottoms of all CF6-80C2 stage-1 disks. The same inspections were added to the routine engine manual inspection requirements for the CF6-80C2 engine. As a result of its investigations into the failure, the US National Transportation Safety Board (NTSB) raised four recommendations addressed to the US Federal Aviation Administration (FAA). Those recommendations included:

- Requirement for operators of CF6-80C2 engines to review maintenance records and conduct an inspection on any HPT stage-1 disks that had blend repairs to the fir tree slot bottoms (recommendation A-00-121).

- Issuance of a flight standards information bulletin informing principal maintenance inspectors and engine overhaul facilities of the circumstances surrounding the disk failure and cracking discovered in other disks (recommendation A-00-122).

- Requirement for the implementation of the eddy-current inspection procedure for the CF6-80C2 disk slot bottoms (recommendation A-00-123)

- The performance of a design review of the CF6-80C2 HPT stage-1 disk to evaluate the adequacy of the current design (recommendation A-00-124).

In response to the NTSB recommendations and its own investigations, the FAA issued airworthiness directive (AD) 2001-10-07 effective 18 June 2001, requiring inspection of nominated CF6-80C2 stage-1 HPT disks in accordance with the engine manufacturer's service bulletin CF6-80C2 SB 72-A1026, at each 'piece-part' exposure. Service bulletin 72-A1026 specified the disk inspection by double etch, double fluorescent penetrant inspection (FPI) and eddy-current inspection and nominated a full, four-stage alkaline cleaning of the disk before each etch and FPI stage.

All corrective actions arising from the third CF6-80 disk failure were specific to the 80C2 series engine only. The additional inspection requirements were not extended to encompass the worldwide fleet of CF6-80A engines.

2 ANALYSIS

2.1 Disk failure

Failure of the number-1 (left) engine from ZK-NBC occurred as a direct result of the rupture of the first-stage high-pressure turbine disk, liberating a large disk section that was uncontained by the engine casing or nacelle. The energetic nature of the fragment release and the resultant gross turbine spool imbalance produced extensive mechanical damage, rendering the engine inoperative.

Disk fracture had initiated from prior fatigue cracking at the base of a turbine blade firtree slot. Fatigue cracking had initiated from the rear corner of that blade slot and propagated radially inward and axially forward, before turning to intersect an adjacent rim-bolt hole. At that stage, the crack was below critical size and incapable of directly causing the disk rupture. Subsequently, the growth of a secondary radial-axial crack from the base of the primary crack enlarged the total defect to a depth of 39 mm, where it reached critical size and initiated the overload failure of the remaining section, with the release of the disk fragment.

2.2 Fir tree slot cracking

The failed first-stage high-pressure turbine disk had sustained a total of three separate fir tree slot bottom fatigue cracks at the time the largest of those caused the disk rupture. All three areas of cracking showed essentially identical origin areas and morphology, suggesting that all had formed in response to the same physical conditions.

Origins

The origin or initiation site of all three disk slot cracks was located at the tangency point between the slot bottom surface and the rear corner (break-edge) profile. In all cases, no isolated anomalous features such as tool marks or material defects were identified at the crack origins, nor was there any evidence of a general disk material deficiency, with the general chemistry, hardness and bulk microstructure comparing favourably with the manufacturers specifications.

A common feature between the cracked slots and numerous other unaffected slots was the presence of numerous PSEF features extending along the rear disk face and around the slot break-edges. These features, which are characterised as surface laps or fissures, are produced as a result of excessive plastic flow of the surface material during shot peening. In a similar manner, the surface plastic flow had also produced an identifiable ridge of material at the rear break-edge tangency points of many disk slots. Microstructurally, the surface plastic flow was associated with a zone of heavily deformed and structurally transformed grains containing numerous fissures, folds and laps. That structure ceased abruptly at the break-edge tangency point, with the predominant slot bottom profile being deformation free.

Shot peening is generally conducted on dynamically loaded parts and components to improve the resistance to fatigue cracking and improve life. Peening acts to generate compressive stresses within the surface material by inducing localised plastic deformation and flow. Published testwork however has shown that the fatigue life

demonstrated by shot peened materials has a high degree of association with the presence or otherwise of shot peen process induced surface damage (in the form of PSEF)[7]. Peening damage and PSEF are produced under process conditions that produce high impact intensities. Contributing variables include shot impact angle, shot size and material, shot velocity and broken particle content within the shot feed. For most materials, testwork has shown that optimum fatigue lives are achieved by relatively low levels of peening intensity; intensities that do not produce PSEF features. Fatigue failure at peening intensities above this optimum intensity range has been shown to be dominated by the presence of PSEF features[1].

With respect to the HPT disk cracking, PSEF type features were observed at all three slot bottom crack origins. While not conclusive in terms of the root cause of the crack initiation (many other uncracked slots had similar features), the physical evidence arising from the investigation supports the peening induced surface damage as being a significant contributory factor to the development of premature fir tree slot fatigue cracking.

[7] 'Quantification of the effects of various levels of several critical shot peen process variables on work-piece surface integrity and the resultant effect on work-piece fatigue life.' R.S. Simpson & G.L. Chiasson, 31 Oct 1988

3 FINDINGS

- The technical investigation of the failed CF6-80A stage-1 high-pressure turbine disk (s/n. MPOP-8478) found that the disk failed as a result of the initiation and growth of fatigue cracking from the rear bottom corner of a turbine blade fir tree slot.

- The disk had developed a total of three slot bottom fatigue cracks at the time of ultimate failure.

- None of the cracks were attributable to any identified erroneous tool or handling damage to the slot bottoms.

- The disk had undergone a repair operation in August-October 1998. The repair was conducted to remove fir tree slot edge nicks and other damage and included blending of the damage followed by shot-peening of the rear slot edges and other areas.

- All of the cracked fir tree slots and several other uncracked slots showed surface microstructural flow and damage that was attributable to the shot peening operation following the 1998 repair.

- The type of surface damage produced (specifically the formation of stress-raising defects known as ‘peened surface extrusion folds’) has been shown to be detrimental to the fatigue life of the affected component.

- The disk had operated for 7,838 hours and through 2,793 cycles following return to service after the August 1998 overhaul.

- The previous CF6-80C2 stage-1 HPT disk failure (September 2000) occurred 1,675 cycles after a similar blending and shot peening repair of disk slots and rear corners.

- The corrective action implemented after the September 2000 disk failure did not encompass the CF6-80A stage-1 HPT disks.

In-flight uncontained engine failure and air turn-back,
Boeing 767-219ER, ZK-NBC

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