



Australian Government

Australian Transport Safety Bureau

ATSB TRANSPORT SAFETY INVESTIGATION REPORT

Aviation Occurrence Investigation – 200605620

Final

In-flight engine malfunction and air turn-back

240 km W Darwin NT

24 September 2006

VH-TJI, Boeing Co. 737-476



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Abstract

On 24 September 2006, during a scheduled passenger service from Darwin, NT, to Denpasar, Indonesia, the left engine of a Boeing Co 737-400 series aircraft sustained a mechanical failure within the first-stage low-pressure turbine (LPT) section. After reducing the engine thrust to minimise vibration and further damage, the flight crew returned the aircraft to Darwin.

Following an analysis overseen by the Australian Transport Safety Bureau, the engine manufacturer found that it was likely that thermally-induced microstructural creep damage had contributed to the blade failure and subsequent damage to the turbine stage. An examination of the engine maintenance and operating records did not reveal any instance/s of hot-starting or significant take-off exhaust-gas temperature exceedence that may have contributed to the premature failure.

A total of seven related LPT stage-one failures had been identified by the engine manufacturer, including two from the subject Australian operator. While work by the engine manufacturer to better understand the issue was continuing, a range of stage-1 LPT blade production batches were identified as possibly being predisposed to premature failure. The engine manufacturer has recommended that LPT blades from the identified batches be removed from service and quarantined at the next maintenance opportunity, pending their further investigation and assessment of the issue.

THE AUSTRALIAN TRANSPORT SAFETY BUREAU

The Australian Transport Safety Bureau (ATSB) is an operationally independent multi-modal bureau within the Australian Government Department of Infrastructure, Transport, Regional Development and Local Government. ATSB investigations are independent of regulatory, operator or other external organisations.

The ATSB is responsible for investigating accidents and other transport safety matters involving civil aviation, marine and rail operations in Australia that fall within Commonwealth jurisdiction, as well as participating in overseas investigations involving Australian registered aircraft and ships. A primary concern is the safety of commercial transport, with particular regard to fare-paying passenger operations.

The ATSB performs its functions in accordance with the provisions of the *Transport Safety Investigation Act 2003* and Regulations and, where applicable, relevant international agreements.

Purpose of safety investigations

The object of a safety investigation is to enhance safety. To reduce safety-related risk, ATSB investigations determine and communicate the safety factors related to the transport safety matter being investigated.

It is not the object of an investigation to determine blame or liability. However, an investigation report must include factual material of sufficient weight to support the analysis and findings. 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.

Developing safety action

Central to the ATSB's investigation of transport safety matters is the early identification of safety issues in the transport environment. The ATSB prefers to encourage the relevant organisation(s) to proactively initiate safety action rather than release formal recommendations. However, depending on the level of risk associated with a safety issue and the extent of corrective action undertaken by the relevant organisation, a recommendation may be issued either during or at the end of an investigation.

The ATSB has decided that when safety recommendations are issued, they will focus on clearly describing the safety issue of concern, rather than providing instructions or opinions on the method of corrective action. As with equivalent overseas organisations, the ATSB has no power to implement its recommendations. It is a matter for the body to which an ATSB recommendation is directed (for example the relevant regulator in consultation with industry) to assess the costs and benefits of any particular means of addressing a safety issue.

About ATSB investigation reports: How investigation reports are organised and definitions of terms used in ATSB reports, such as safety factor, contributing safety factor and safety issue, are provided on the ATSB web site www.atsb.gov.au.

FACTUAL INFORMATION

Introduction

At around 2230 Central Standard Time¹ on 24 September 2006, the flight crew of a Boeing Co. 737-476 aircraft, registered VH-TJI, operating a scheduled passenger flight from Darwin, NT, to Denpasar, Indonesia, noted a significant increase in the vibration levels indicated by the number-1 (left) engine. At that time, the aircraft was climbing through an altitude of 34,000 ft and was approximately 240 km west of Darwin.

After completing the non-normal checklist (NNC) for high engine vibration and reducing the engine to idle thrust, the crew declared a 'PAN'² condition to air-traffic control and advised of their intention to return to Darwin, requesting full aerodrome emergency preparation. The aircraft landed at 2309.

A preliminary inspection of the number-1 engine by the operator's engineering staff revealed evidence of a mechanical failure within the low-pressure turbine assembly. As a result, the engine was removed from the aircraft.

Technical investigation

Engine examination

The damaged engine (model CFM56-3C1, serial number 722113, Figure 1) was transported to the workshops of Lufthansa Technik, Hamburg, Germany, where it was disassembled and examined in the presence of a representative of the German Federal Bureau of Aircraft Accident Investigation (BFU), acting on behalf of the Australian Transport Safety Bureau (ATSB). Representatives of the engine manufacturer (CFM International) and the aircraft operator were also present during the disassembly.

¹ The 24-hour clock is used in this report to describe the local time of day, Central Standard Time (CST), as particular events occurred. Central Standard Time was Coordinated Universal Time (UTC) +9.5 hours.

² General broadcast radio code indicating uncertainty or alert, but not at level of MAYDAY.

Figure 1: Left engine from VH-TJI, serial number 722113



The region of failure was confirmed as the low-pressure turbine (LPT) section of the engine (Figure 2A), with all first-stage LPT blades having fractured through the aerofoil section between the blade platform and mid-span (Figures 3 and 4). Several of the remnant blade sections showed a degree of axial twisting and in-plane curvature opposite the direction of rotation (Figure 5), with the majority also showing random mechanical nicks, cracks and indentations associated with multiple and repeated impacts against the liberated debris. Evidence of prior repair and re-work blending was noted along the leading edges of some blades (Figure 6). However, there was no evidence of a correlation between the planes of fracture and the areas of re-work. The LPT stage-1 air seals and adjacent guide vanes had sustained extensive damage associated with the LPT blade rupture.

Other than the damage associated with the passage of the blade debris, the examination found no other evidence of abnormalities within the engine turbomachinery or accessory equipment. The aircraft operator did not report any associated operational problems that preceded the malfunction event.

Figure 2: Schematic cross-section of the CFM56-3 series engine. The turbine section is shown in greater detail in figure 2A

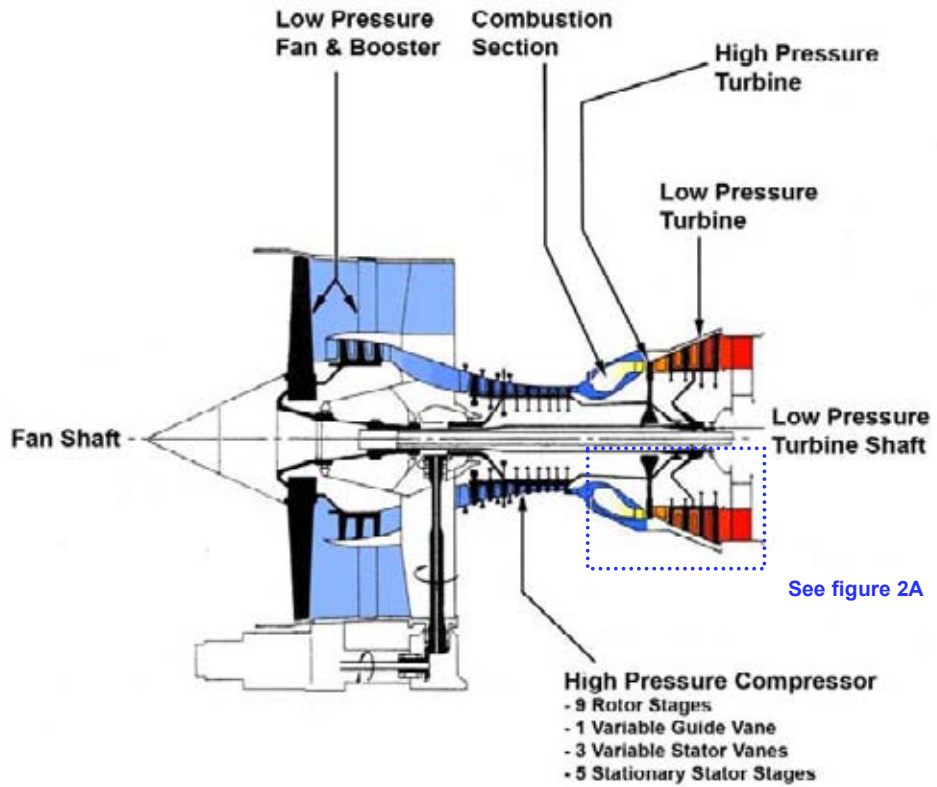


Figure 2A: Detailed view of CFM56-3 turbine section. Location of the stage-1 LPT is shown

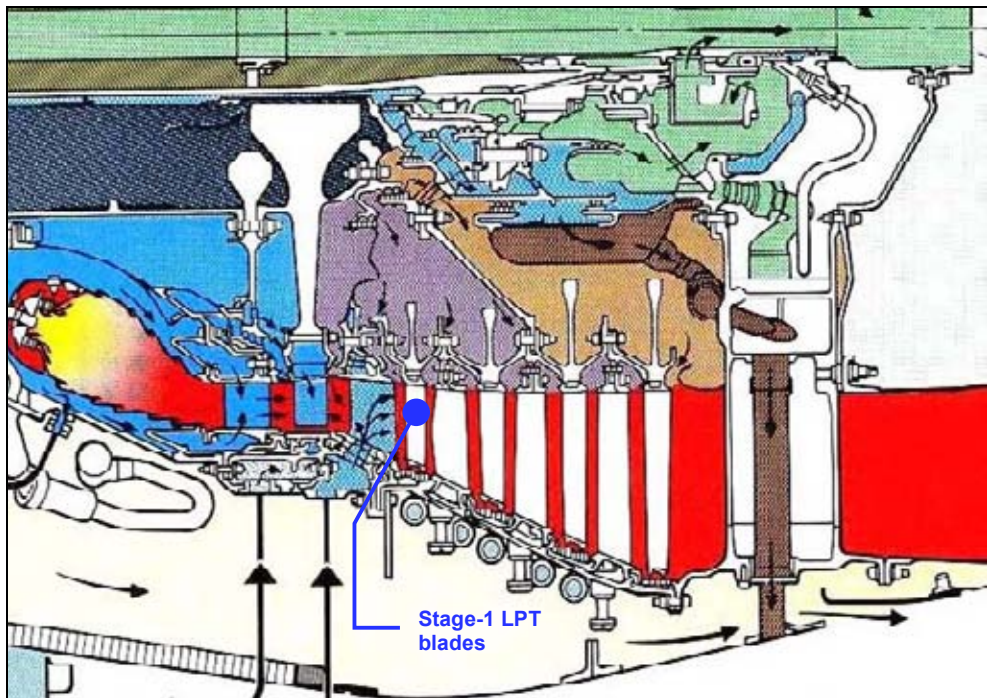


Figure 3: Damaged stage-1 LPT blades. View looking towards the rear of the engine



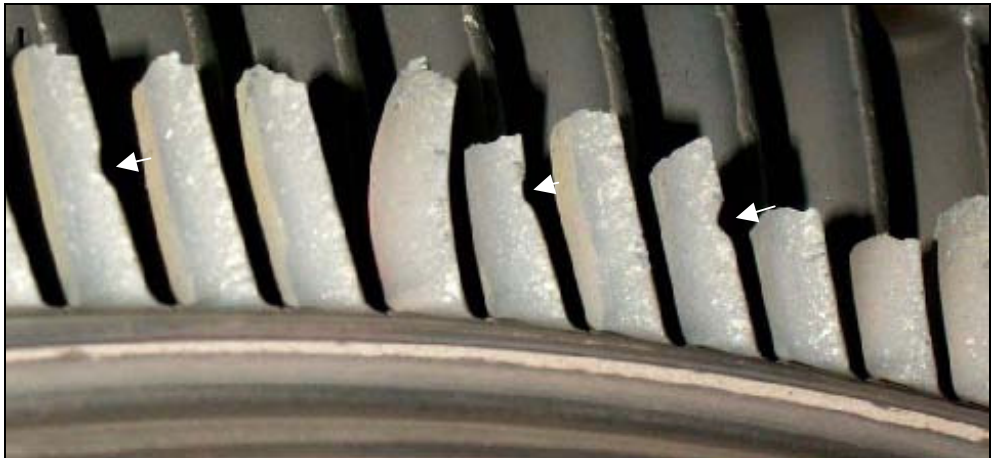
Figure 4: Stage-1 LPT disk and blades, with accumulated blade debris



Figure 5: Damaged LPT stage-1 blades. Note the variation in colouration and curvature shown (example arrowed)



Figure 6: Leading edges of damaged LPT blades, showing areas of prior repair blending (arrowed)



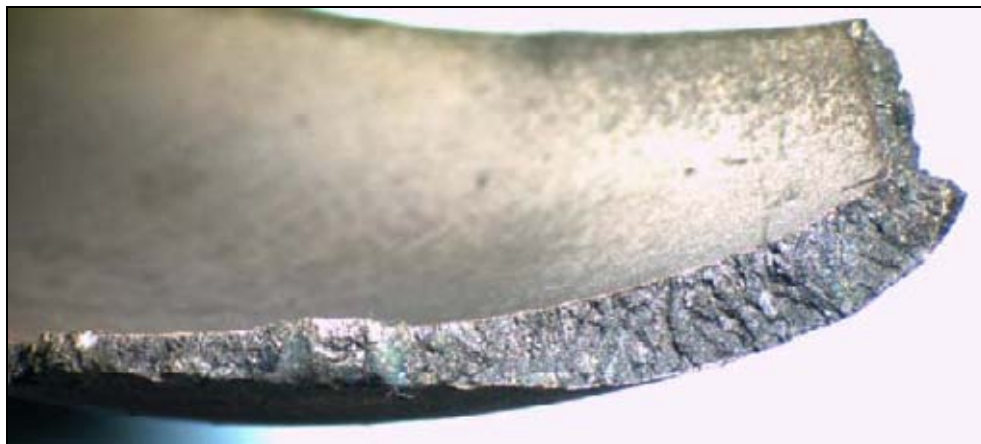
Blade visual examination³

All LPT stage-1 blades were removed from the disk for characterisation of the fractures. All fracture surfaces presented an irregular, semi-crystalline appearance with a vague dendritic patterning that was typical of impact overload fractures in cast superalloy components (Figure 7). None of the fractures or associated cracking showed any evidence of pre-existing or progressive (fatigue) cracking. All LPT stage-1 blades displayed damage typical of the cascading collapse of the blade set

³ Carried out by Lufthansa Technik AG in cooperation with a representative from CFM International.

and associated debris impacts. None of the blades or adjacent guide vanes showed evidence of localised gross oxidation or incipient melting from over-temperature effects.

Figure 7: Typical LPT stage-1 blade fracture surface



A variation noted in the surface colouration between blades from the stage-1 LPT was attributed to the re-coating of some blades using a specific aluminide product (*Sermaloy JTM*) following repair operations. A physical variation was also noted, with many of the *Sermaloy JTM* re-coated blades presenting considerably less aerofoil section twisting and distortion when compared with the unrepaired blades (Figure 5).

Blade microstructural examination³

Twelve blades from the stage-1 LPT set were selected for sectioning and metallographic examination by Lufthansa Technik, representing six examples each of the twisted and straight blades. Initial examination of several transverse sections through the remaining blade aerofoils revealed a distribution of fine gamma-prime⁴ precipitate within a matrix of gamma phase (Figure 8). The gamma-prime phase showed an observable coarsening and coalescence towards the leading-edge and mid-chord positions along the aerofoil length, together with some evidence of gamma-prime re-precipitation at the grain boundaries (Figure 9). An analysis of the microstructures by Lufthansa Technik and CFM International led to the reported conclusion that the blades had sustained a *rapid and sectorial previous overheating⁵*, producing a partial dissolution and subsequent re-precipitation of the gamma-prime phase upon cooling. It was further concluded that it was *likely that a number of 1st stg. LPT blades of the failed set exhibited different temperature exposure histories and were installed / operated in a condition of already reduced strength⁶*.

4 *Gamma-prime* is a microstructural constituent found in nickel-based heat-resistant alloys, which provides an enhanced creep resistance and strengthening effect when distributed as a fine precipitate.

5 Excerpt from LHT Hamburg communication dated 15/11/2006.

6 Lufthansa Technik AG HAM TQ/M Report 2006 625.

Reports received from both Lufthansa Technik and CFM International⁷ both indicated the absence of any evidence of tertiary microstructural creep⁸ damage within the examined blade sections. The persistence of sigma phase beneath the blade surface coating was cited as evidence that the blades had not experienced temperatures above 1050°C.

Figure 8: Characteristic microstructure of the stage-1 LPT blade material

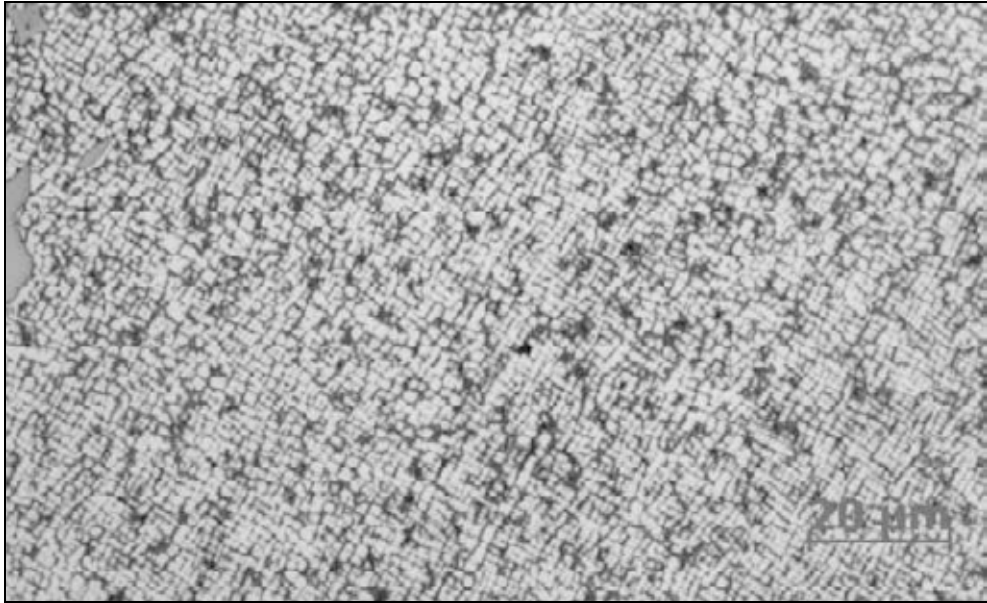
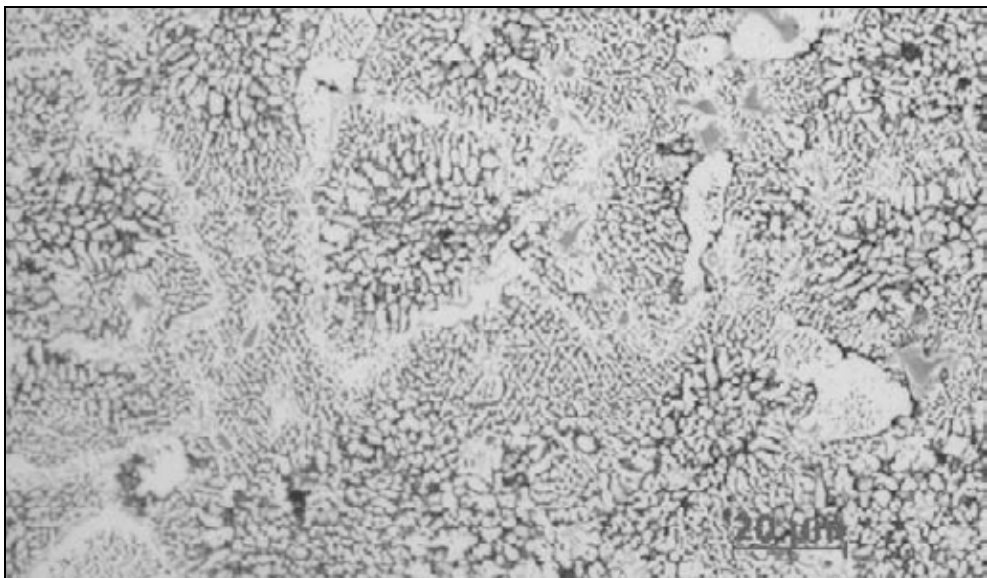


Figure 9: Thermally-degraded LPT blade material



7 Presentation document dated January 16, 2007.

8 Tertiary creep - an advanced stage of creep damage, where physical voids and separations begin appearing within the material microstructure.

Engine history

The engine had operated for a total of 51,233 hours / 30,912 cycles since new. The low-pressure turbine module (part number CFM56-3EMU54X, serial number 54X24602) had accumulated 11,894 hours / 7,440 cycles since the last complete disassembly and overhaul, which was undertaken in July 2002. The last engine shop visit (June 2006) included a module 'check and repair' workscope, with the engine having operated for 590 hours and through 431 cycles since that time.

A study of the engine's on-wing history as provided by the operator, revealed a total of 19 exhaust-gas temperature (EGT) alert events reported by the aircraft communications and automatic reporting system (ACARS), between 12 July 2002 and 24 September 2006. All EGT alerts occurred prior to the June 2006 shop visit, when the engine was fitted to another aircraft. Of those alerts, the majority were for EGT exceeding 930°C during takeoff. A graphical analysis of the alerts (Appendix A) shows an increase in frequency and peak EGT reported, reflecting the reducing EGT margin⁹ as the time since last overhaul increased. Exhaust gas temperature limits for the CFM56 engines were published in the aircraft maintenance manual, with limits for starting and operation specified in terms of time spent above a particular temperature. Maintenance actions ranging from visual (borescope inspection), to engine removal, were prescribed by the maintenance manual, on the basis of the extent of time the engine spent above a limiting EGT value. The manual also required the operator to ascertain the likely cause of each EGT exceedance event. In terms of event frequency and recurrence, limits were specified before engine removal was required. While the engine had sustained a number of EGT exceedances that required engine inspections, the number and magnitude of the events were such that the engine maintenance manual did not require further maintenance action.

Turbine blade history

Discussions with the aircraft operator revealed that CFM56 stage-1 LPT blades were not considered by the manufacturer to be a life-limited component, and as such, the blades were not individually serialised and tracked with reference to their accumulated time in service. Upon each LPT module 'reconditioning' overhaul, the blades were removed and sent to a third-party for inspection and repair or rejection. LPT disks were assembled with blades drawn from the operator's pool of new and/or reconditioned items, meaning that any given disk would be loaded with blades of varying and unknown thermal histories.

History of LPT failures

Information provided by the engine manufacturer showed that world-wide, between July 2006 and February 2007, seven CFM56-3 engines had sustained an LPT stage-1 blade failure, including the earlier failure of an engine from a sister aircraft to VH-TJI¹⁰. Despite the reported lack of evidence of tertiary creep damage within the blades examined from engine 722113, the manufacturer concluded that creep

⁹ Temperature differential between measured operating EGT values and the prescribed upper EGT limit for serviceable engine operation.

¹⁰ VH-TJU number-2 engine, serial number 722387, 27 July 2006.

rupture was the most likely failure mode affecting all seven engines. Significantly, it was also reported that for those instances where an initiating blade failure was identified, those blades had all originated from a related range of blade production batches.

Exemplar blade material examination

A selection of 17 stage-1 LPT blades from the operator's unserviceable stock was obtained by the ATSB for metallurgical characterisation (Figure 10). The thermal / operational histories of the blades were unknown, however the part number (301-330-114-0) was the same as the blades installed in engine 722113. Three of the blades were selected for examination, with sections cut and polished axially through the blade root and transversely through the aerofoil mid-chord position.

Figure 10: LPT blades received for examination



The three blades examined were comparable in respect of the level of thermally-induced changes within the gamma-prime microstructure. When compared against baseline structures within the root of the blades (Figure 11), the gamma-prime phase clearly showed a coalescence effect (Figure 12). However, when examined against representative structures for similar nickel-superalloy materials, the degree of coalescence and phase growth was considered to be within the ranges expected for normal blade operation. As such, the blades did not present any direct evidence of overheating. The clear presence of remnant sigma phase that is formed within the base metal immediately beneath the surface coating layer when the coating is first applied, was evidence that the blade temperatures had not exceeded 1050°C (Figure 13). At temperatures above 1050°C, the sigma phase rapidly breaks down and solutionises within the gamma matrix, and is thus an indicator of transient overheating events.

Figure 11: Typical baseline structure of the exemplar LPT blades (Kalling's etch)

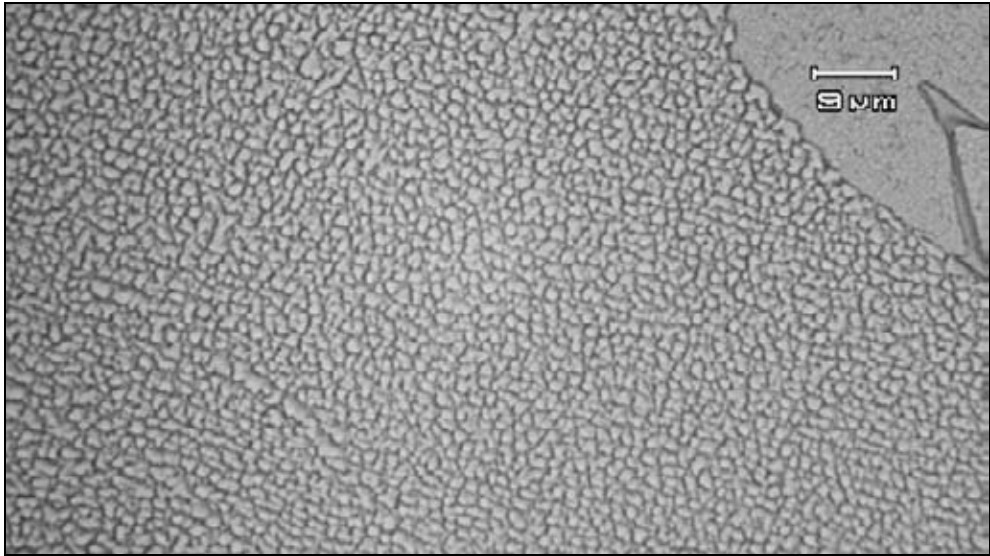


Figure 12: Thermally affected blade material, showing coalescence of the gamma-prime (light) phase (Kalling's etch)

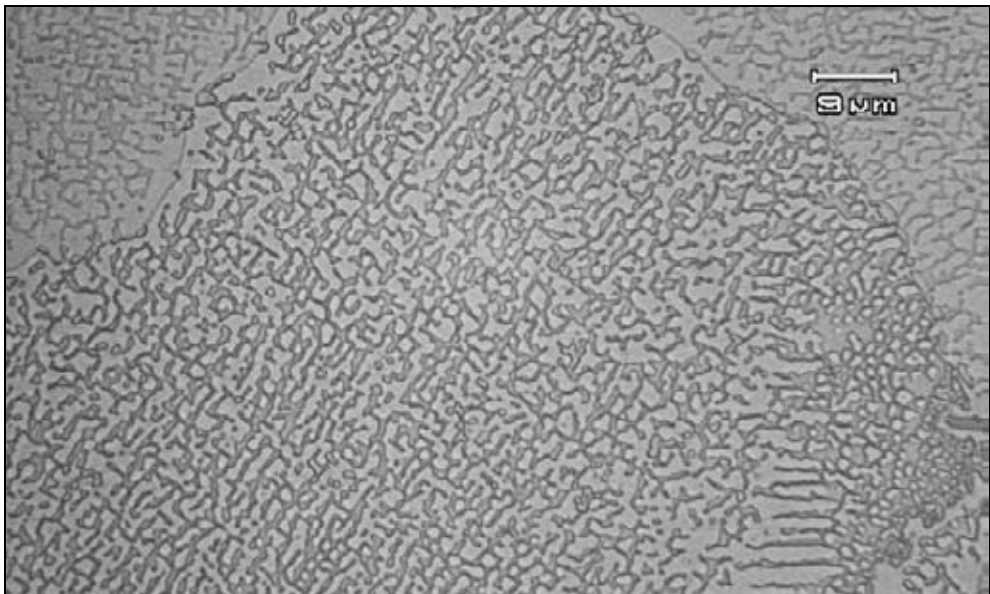
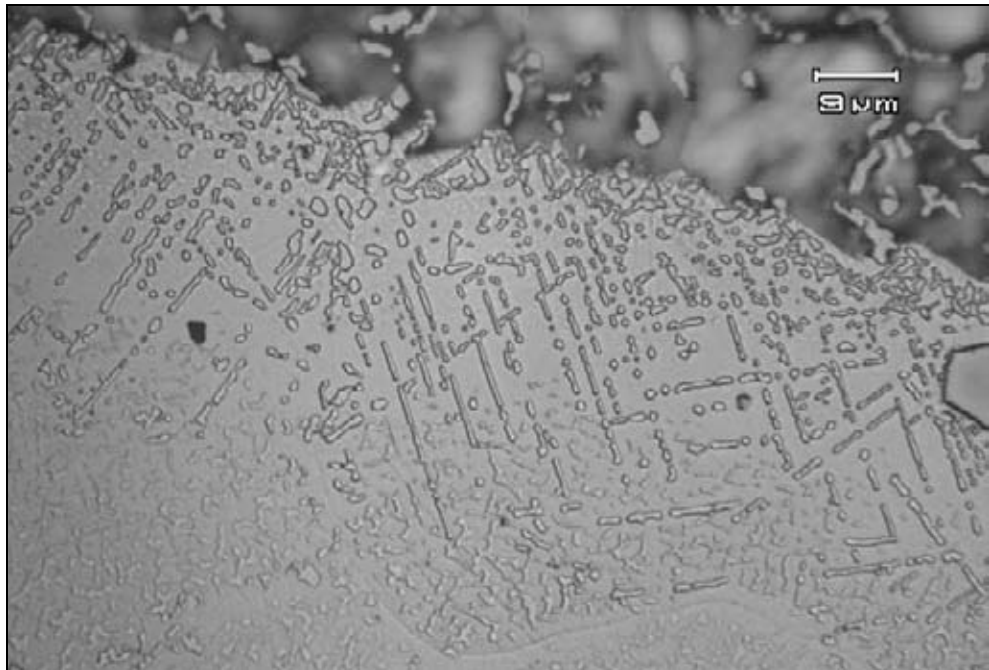


Figure 13: Surface sigma-phase (needles) remaining in the LPT blade microstructure (Kalling's etch)



General microscopic examination of the blade sections revealed several additional noteworthy features, including internal solidification voids/micro-shrinkage within the aerofoil sections (Figure 14), full-thickness coating cracks and grain-boundary oxidation (Figure 15), internal intergranular cracking (Figure 16) and limited surface sulphidation in the uncoated blade areas (Figure 17). While potentially injurious to the blade integrity, none of the blades showed any evidence of incipient failure or breakdown as a result of the anomalous features.

Figure 14: Micro-shrinkage and voids within an exemplar LPT blade section (unetched)

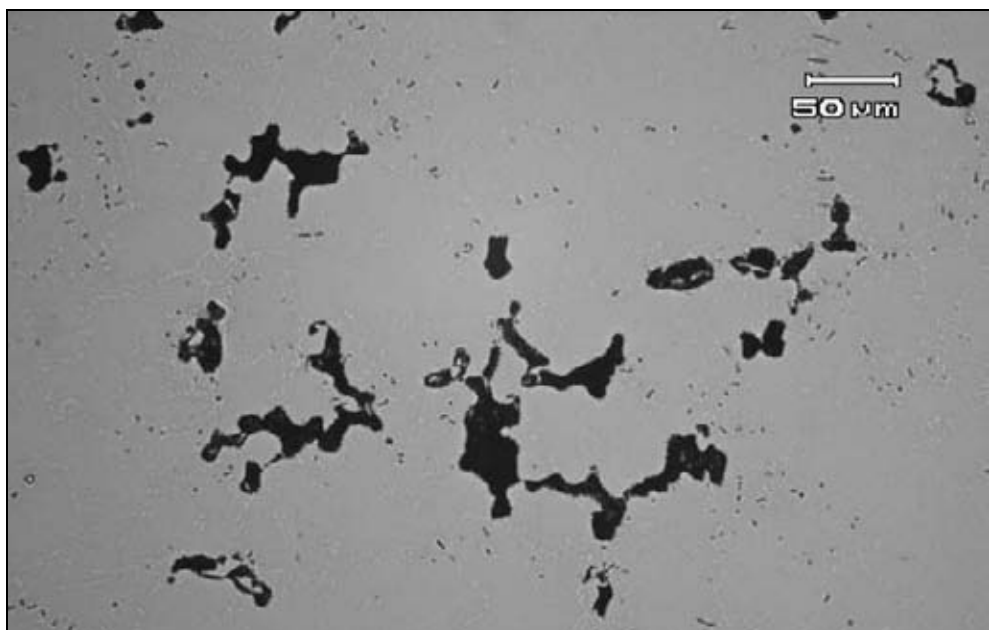


Figure 15: Shallow sub-surface cracking and oxidation within an exemplar LPT blade (unetched)

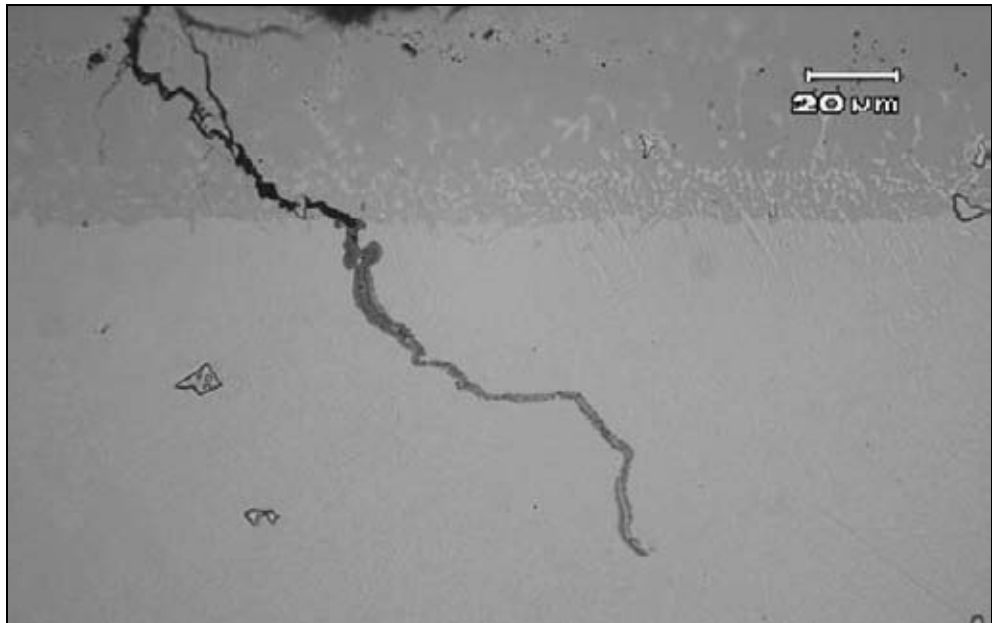


Figure 16: Internal and surface intergranular cracking within an exemplar LPT blade (unetched)

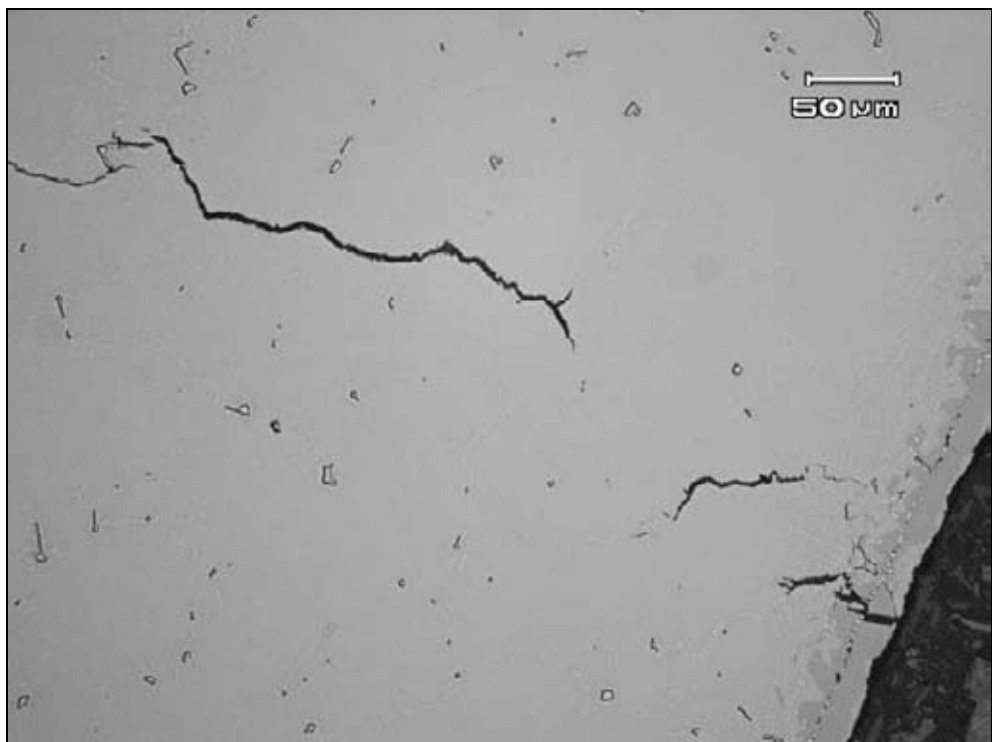
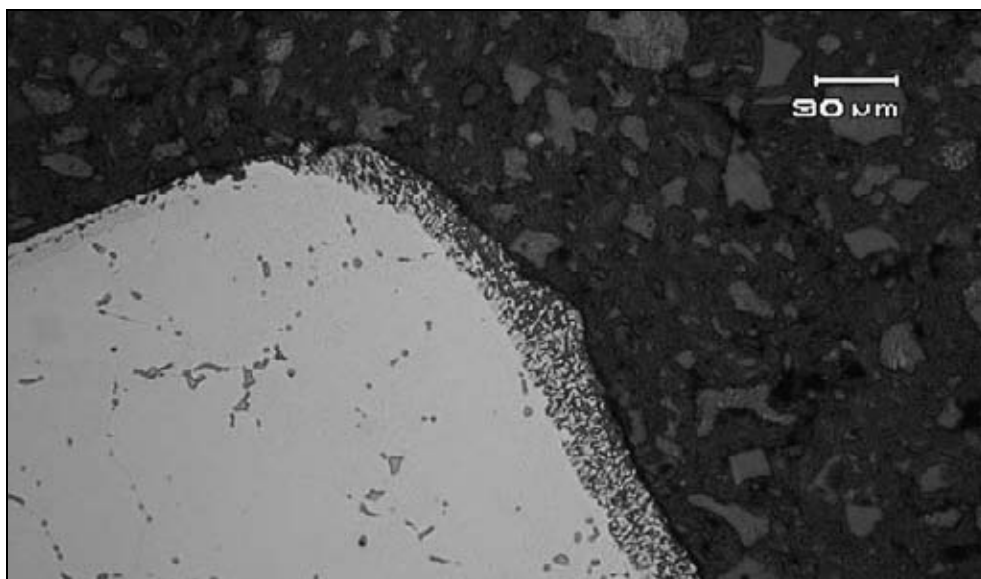


Figure 17: Root surface sulphidation exhibited by an exemplar LPT blade (unetched)



Recorded data

The aircraft was fitted with a Fairchild / L3 FA2100 solid-state flight data recorder (FDR), from which the ATSB obtained a complete download of the raw data after the occurrence flight. The FDR contained approximately 42 hours of data, which represented the occurrence flight and the preceding 25 flights.

Engine vibration monitoring system

Each of the aircraft's CFM56-3 engines included an engine vibration monitoring system. Each system comprised two accelerometers (vibration sensors) located on the No. 1 bearing support and the turbine rear frame, a cockpit vibration indicator and a signal conditioner located in the avionics compartment.

By tracking fan / LPT (N1) and core (N2) engine speeds, the signal conditioner can filter for:

- fan vibration (FAN)
- low-pressure turbine (LPT) vibration
- high-pressure compressor (HPC) vibration and
- high-pressure turbine (HPT) vibration.

The highest vibration value for each engine is displayed on the respective cockpit indicator. The vibration value is dimensionless and a maximum value of 5 units can be displayed. A maximum value of 10 units can be recorded by the FDR.

Abnormal vibration can be caused by a variety of circumstances, including compressor or turbine blade damage, bearing distress, rotor imbalance, improperly functioning accessory drive gears or failure of a rotating part in one of the engine-mounted accessories.

Occurrence flight

The information from the FDR enabled the ATSB to develop a sequence of events history for the occurrence flight and engine malfunction.

At 2213:52, VH-TJI departed from Darwin Airport on runway 29. During the climb, vibration values recorded for the LPT of the right engine were generally higher than the values recorded for the left engine (e.g. 1.5 for the right engine versus 0.5 for the left engine). Those general indications were consistent across the data recorded from the previous flights.

At 2225:13, while climbing through 26,000 feet, the first irregular engine vibration values were evident. There was a step increase (from 1.16 units to 2.80 units) in the LPT vibration for the left engine. After the initial step increase, the LPT vibration values increased over the next 8 seconds, reaching 4.20 units. There was no change in the LPT vibration for the right engine over this period.

Examination of the other left engine parameters at the time the LPT vibration increased showed that there were corresponding small increases in fuel flow and EGT. This was evidence that the step increase in vibration was consistent with an internal engine event, and that the increase in vibration levels from the left engine was a genuine indication. The other 25 flights recorded by the FDR were examined and none showed a similar step increase in LPT vibration values for either engine.

After reaching 4.20 units, the LPT vibration values for the left engine began to trend downwards, reaching a minimum value of 3.24 units by 2229:46.

At 2229:59, as the aircraft approached the top of climb at FL340 (34,000 ft), both thrust lever angles were reduced slightly. Coincidentally, the left engine N1 decreased and split from the N1 values for the right engine. EGT for the left engine began to increase while EGT for the right engine began to decrease.

LPT vibration values for the left engine stayed at 3.6 units until 2230:02. After this time, LPT vibration values jumped to 6.8 units and then began to further increase, reaching 10.0 units indicated (maximum recorded value) at 2230:14. Figure 18 presents the vibration data from both the left and right engines of VH-TJI from 2229 to 2232.

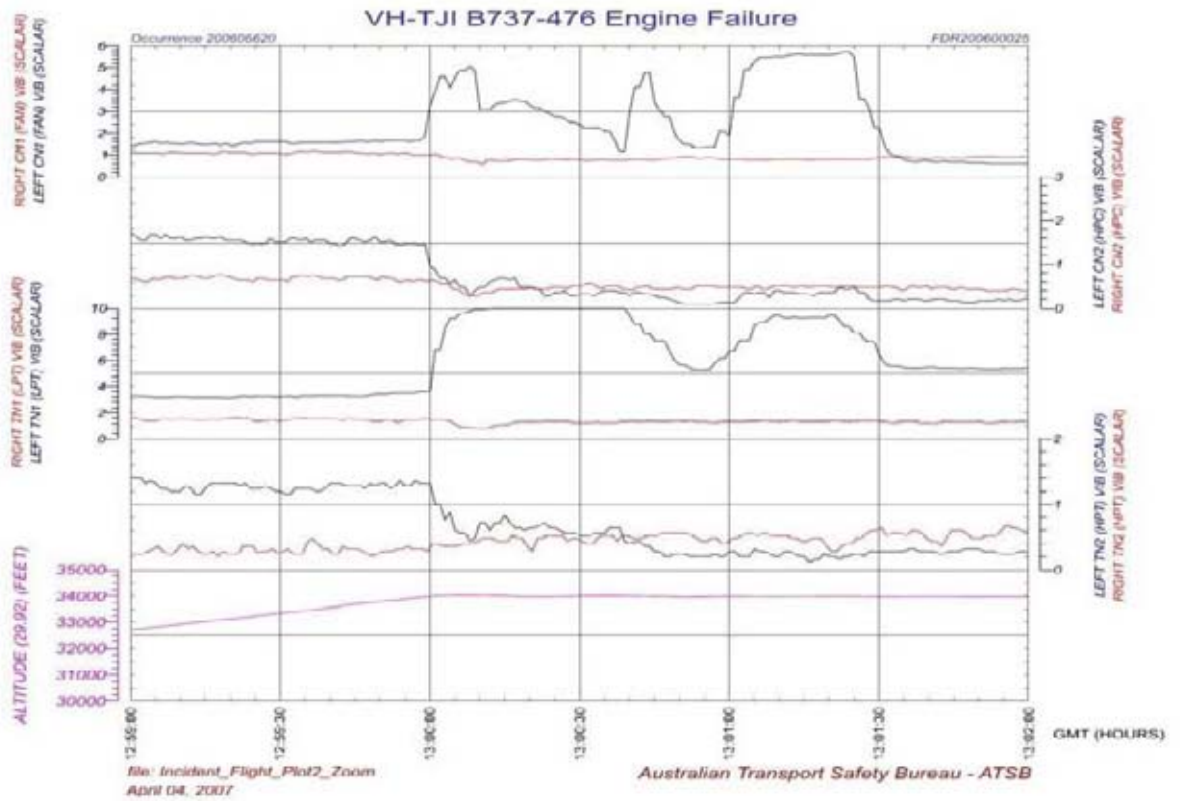
At 2230:21, the auto-throttle disengaged and by 2231:33 left engine thrust had been reduced to idle (N1 of 40%). The aircraft began the descent at 2232:44, and the left engine LPT vibration remained at around 5 units for the rest of the flight.

Previous flights

The FDR had recorded data from the incident flight and the previous 25 flights across the period 20 to 24 September 2006. Recorded EGT values were checked for exceedences during flight and during engine start for all flights. Due to the aircraft systems configuration, the FDR did not commence recording until the right engine had started and was operating normally. As such, the check for EGT exceedences on engine start only applied to the left engine.

No evidence of an EGT exceedance on engine start (>725°C) or in-flight (>895°C) was observed in the FDR data.

Figure 18: Graphical presentation and comparison of the left and right engine vibration parameters during the engine malfunction event



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ANALYSIS

Engine malfunction

The left engine malfunction sustained by VH-TJI after the aircraft departed from Darwin was the result of a mechanical breakdown within the engine's stage-1 low-pressure turbine assembly. The turbine blade failures were characteristic of a cascading rupture, where an initiating blade failure or event triggers multiple consequent blade forced failures from impact with debris confined within the turbine space. The investigation was unable to identify the exact event that precipitated the turbine failure, however there was no evidence that fatigue cracking or other local blade defects had contributed.

Turbine blade failure

The engine manufacturer's investigation of seven similar LPT stage-1 failures (including this occurrence), concluded that in all instances, microstructural creep was the suspected mechanism that had produced the initial blade failures. Defined as *the progressive plastic deformation of a material under the influence of an external stress below the materials' normal yield point*, sustained creep under operating loads can produce blade extension that exceeds the tolerable limit at the shroud/seal interface. Excessive shroud interference could lead to unstable collapse and break-up of the blade set, such as sustained by engine 722113.

Microstructural creep is a material-time-temperature dependent phenomenon. The IN100 alloy from which the LPT stage-1 blades were produced uses a precipitation-strengthening mechanism to endow the blades with creep resistance at the elevated temperatures of operation. Over a period of exposure, the microstructural precipitate (gamma-prime phase) will progressively coalesce, becoming coarser and consequently reducing the creep resistance of the alloy. The rate of coalescence is a function of the time spent at temperature, and is non-linear, inasmuch as the microstructural degradation proceeds more rapidly above the prescribed temperature limits for the engine. It thus generally follows, that turbine blades will exhibit an increased probability of creep-related failure as they accumulate service exposure. Transient thermal events that may be indicated by EGT exceedences, would have a cumulative damaging effect.

Currently, LPT blades are maintained on a physical condition basis, and as the accumulated service lives are not tracked individually, it is not possible to identify those blades which have accumulated a greater time in service. Given that the creep performance of a blade is dependent on its initial (baseline) microstructure, as well as its thermal history, the engine manufacturer's identification of a range of blade batches from which components have failed prematurely, may serve as a mechanism by which engine operators are able to reduce the probability of future LPT stage-1 breakdown events.

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FINDINGS

Context

During a scheduled international passenger flight from Darwin to Denpasar, Indonesia on the 24 September 2006, the left engine of a Boeing Co. 737-476 aircraft (VH-TJI) malfunctioned when multiple stage-1 low-pressure turbine (LPT) blades fractured and separated from the rotating assembly. The engine was reduced to idle thrust to minimise the subsequent vibration and the aircraft was safely returned to Darwin.

From the evidence available, the following findings are made with respect to the engine malfunction sustained by VH-TJI, and should not be read as apportioning blame or liability to any particular organisation or individual.

Contributing safety factors

- The left engine of VH-TJI was significantly limited in its operational functionality by the failure of the stage-1 LPT turbine assembly.
- The stage-1 LPT assembly failure was precipitated by the creep extension and/or rupture of LPT blades, brought about by the thermally-induced microstructural degradation of the blade aerofoil material.
- The engine manufacturer has reported that certain production batches of stage-1 LPT blades (including blades that were installed in the left engine of VH-TJI at the time of failure) may be predisposed to premature creep-related failure, as a result of microstructural or chemical composition issues. *[Safety issue]*

Other key findings

- The engine manufacturer does not require the service life and thermal/operational history of CFM56-3 engine LPT blades to be individually recorded. The blades do not have a manufacturer-prescribed life limit and are maintained on the basis of their physical condition.
- Physical inspection of the stage-1 LPT blades during overhaul does not identify cumulative thermal damage to the blade material.

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SAFETY ACTIONS

The safety issues identified during this investigation are listed in the Findings and Safety Actions sections of this report. The Australian Transport Safety Bureau (ATSB) expects that all safety issues identified by the investigation should be addressed by the relevant organisation(s). In addressing those issues, the ATSB prefers to encourage relevant organisation(s) to proactively initiate safety action, rather than to issue formal safety recommendations or safety advisory notices.

All of the responsible organisations for the safety issues identified during this investigation were given a draft report and invited to provide submissions. As part of that process, each organisation was asked to communicate what safety actions, if any, they had carried out or were planning to carry out in relation to each safety issue relevant to their organisation.

Depending on the level of risk of the safety issue, the extent of corrective action taken by the relevant organisation, or the desirability of directing a broad safety message to the aviation industry, the ATSB may issue safety recommendations or safety advisory notices as part of the final report.

CFM International

Certain batches of stage-1 LPT blades for the CFM56-3 engine may be susceptible to premature creep-related failure in service

Safety issue

The engine manufacturer has reported that certain production batches of stage-1 LPT blades (including blades that were installed in the left engine of VH-TJI at the time of failure) may be predisposed to premature creep-related failure, as a result of microstructural or chemical composition issues.

Action taken by CFM International

The engine manufacturer has recommended that LPT blades from the identified batches be removed from service and quarantined at the next maintenance opportunity, pending their further investigation and assessment of the issue. They also indicated that the development of new criteria is being considered for the assessment of blades at overhaul, with parameters such as blade length being considered as possible indicators of the metallurgical condition of the components.

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APPENDIX A: HISTORY OF REPORTED EGT OVER-TEMPERATURE ALERT EVENTS ENGINE 722113

