Uncontained engine failure during take-off
with a Fly Air Airbus A300-B4, registration TC-FLF,
Amsterdam Airport Schiphol, June 29, 2005

The Hague, may 24, 2007, Occurrence number 2005094

THE DUTCH SAFETY BOARD

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In accordance with Annex 13 to the Convention of Chicago as well as Directive No.94/56/EC of the Council for the European Communities, which established the fundamental principles governing the investigation of civil aviation accidents and incidents, the investigation of the Dutch Safety Board is not intended to apportion blame or liability.

N.B:
This report is published in the Dutch and English languages.
In the event of conflict in interpretation, the English text will be deemed binding

1 FACTUAL INFORMATION

1.1 GENERAL

Place	:	Amsterdam Airport Schiphol
Date and time	:	June 29, 2005, 22:33 local time
Airline Company	:	Fly Air
Flight number	:	FLM 1632
Aircraft	:	Airbus A300-B4
Registration	:	TC-FLF
Engines	:	General Electric CF6-50C2, serial number failed engine 528187
Crew/passengers	:	14/298, no injuries
Type of flight	:	Commercial passenger flight
Phase of flight	:	Take-off
Type of occurrence	:	Uncontained engine failure

1.2 HISTORY OF FLIGHT

On June 29, 2005 a twin engine Airbus A300-B4 of the Turkish operator Fly Air, registration TC-FLF, landed at Amsterdam Airport Schiphol (EHAM) at 20:45 local time (LT). The flight originated from Ankara (Turkey) under flight number FLM 1631, and was on blocks at 20:50 LT. No technical anomalies were reported and no entries had been written in the Flight and Maintenance Log.

According to the captains report start up and push back clearance was received at approximately 21:55 LT. The flight was from Amsterdam to destination Kayseri (Turkey) under flight number FLM 1632, with 298 passengers and 14 crew members on board. The aircraft taxied to runway 36L where it had to hold short of the runway.

At approximately 22:31 LT the aircraft lined up on the runway. No irregularities to aircraft or engines were reported till this phase of flight. At approximately 22:32 LT flight FLM 1632 was cleared by air traffic control (ATC) for take-off runway 36L and the aircraft started to accelerate. The captain indicated that the decision speed V1 was 152 knots.

Flight data recorder (FDR) readout showed that during the take-off roll both engines stabilized at approximately 105% N1. During the further acceleration of the aircraft an explosion was heard on the left side of the aircraft and according to the pilots the left engine instrument parameters of dropped to zero. The take-off was rejected. FDR information revealed that the rejection was at 142 knots, reportedly without further complications.

At approximately 22:33 LT, ATC was informed that the take-off was rejected. Fire brigade assistance was offered and accepted. After arrival of the fire brigade tire and brake cooling operations were carried out, and after completion of all the safety measures the aircraft was pulled back to the parking area.

During the communication between ATC and the cockpit crew immediately following on the event, the crew reported that they had seen "… an animal that had crossed the airplane and jumped into the engine".

Inspection of the left engine revealed severe damage to the engine fan and fan inlet duct. One fan blade part had separated from just below the mid-span shroud area. A piece of debris had penetrated and exited the acoustic panels and engine cowling (see figure 1 and 2). The aircraft fuselage showed a few little dents. The airport authority mentioned in its incident report that a bird controller found various aircraft parts on the runway.

Information from the cockpit crew
In relation to the event the captain's report says that on the left side of the plane a very high level explosion was heard and the left engine instrument parameters dropped to zero.

Some of the recorded communication between the TC-FLF and ATC was reviewed. It appeared that the crew reported to have seen "… an animal that had crossed the airplane and jumped into the engine". The Dutch Safety Board asked (about three weeks after the event) the pilot who had reported this to provide more detail of what he had seen. In summary the pilot stated that it was rather a guess than an observation since some shadows were observed on the left side just before the engine exploded. Given it a second thought he believed that the shadows the crew had observed were mainly due to a fireball in the dark.

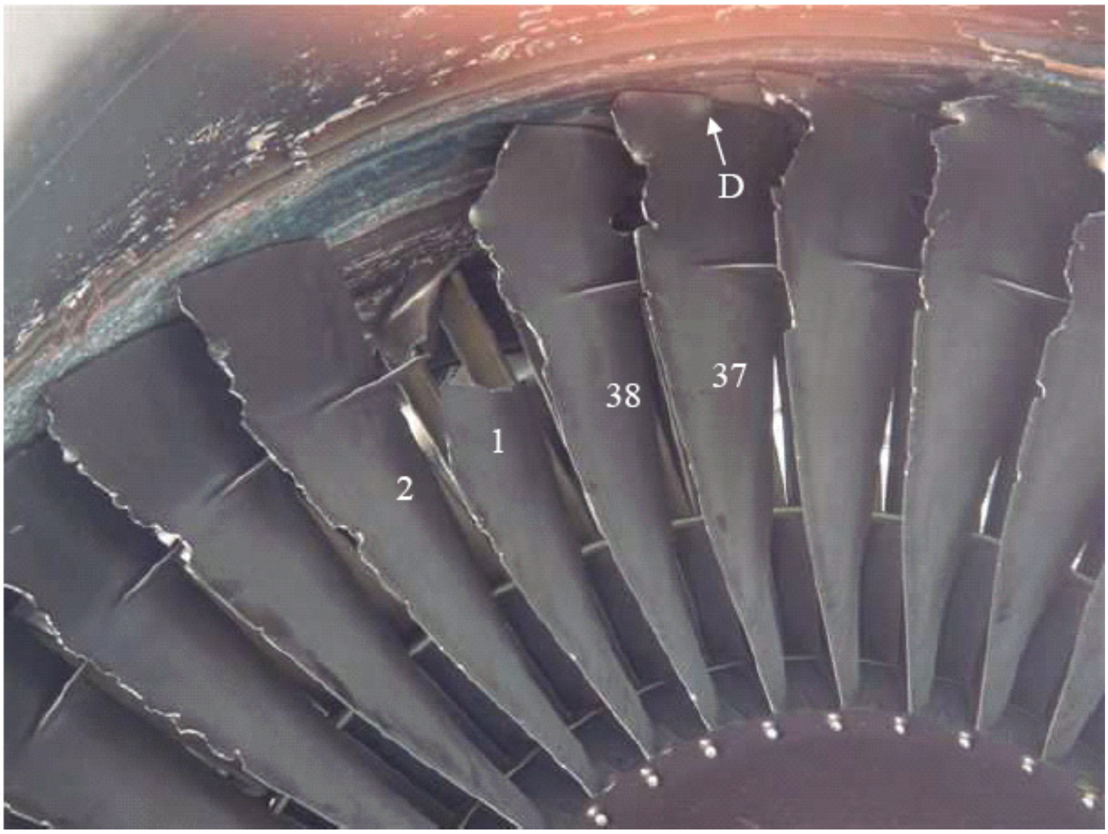

Figure 1: The broken fan blade – labelled 1 - and adjacent blades (seen from the engine inlet)

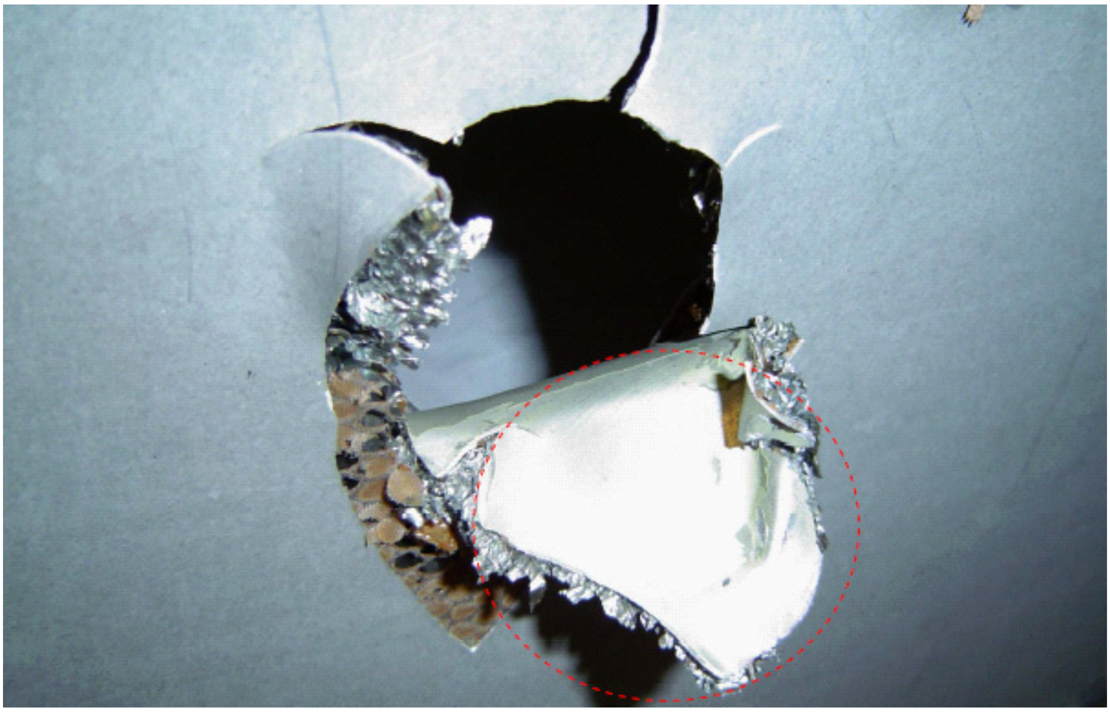

Figure 2: Hole in fan cowling as seen from outside. The encircled area was investigated with EDX

Figure 3: Cusps in leading edges of fan blades 1 and 38

1.3 Investigation

1.3.1 General
The event was considered as a serious incident as the engine failure appeared to be uncontained. These failures pose an immediate risk upon passengers and crew onboard the aircraft. Apart from the loss of the failed engine this sequential damage to the aircraft can also seriously affect the level of safety as separating engine parts may hit other systems and parts, thereby degrading their functioning and reliability.

Furthermore, this Fly Air incident was subject to media attention. The event occurred during a period that the safety level of a number of Turkish charter operators had been questioned in the media within The Netherlands. Turkish operators, including Fly Air, were under intensified supervision of the Civil Aviation Authorities of The Netherlands. In that light this investigation might also reveal to what extent this incident proved to be relevant to the social concern[1] about Turkish operators within The Netherlands.

In the course of the investigation the following main activities were carried out:
- visual inspection;
- bore scope inspection;
- ultraviolet light inspection;
- metallurgical failure analysis;
- photograph analysis;
- other comparable instances;

1.3.2 Circumstances affecting the engine investigation
The aircraft was parked outside for a few days before the engine was removed. The first visual inspection by the Dutch Safety Board was carried out approximately fourteen hours after the event. Bird ingestion is one of the common factors for this type of incidents. Single small bird ingestions with high by-pass engines might not always cause obvious evidence. Little remnants of organic residue may fade when it is exposed too long to e.g. drying air for several hours or even days or weeks.

Once the engine was removed it took a couple of days before it was put in quarantine. Finger prints on the fan blades and foot steps in the fan inlet duct indicated that since the incident people had had access to the engine. The effect of this on the investigation results is not clear. However, this usually is not to the benefit of the investigation as it may destroy evidence. An ultraviolet light inspection was performed about two weeks after the incident.

The conditions for the investigation where it concerns access and space, light and the absence of electrical power and the limitations to create sufficient obscurity (for black light inspection) did not contribute to adequate conditions for performing a black light and an additional visual inspection in the engine storage cell.

The moment that the engine failure occurred could not be found on the cockpit voice recorder (CVR) as it remained under power for longer than 30 minutes after the event. This blocked the possibility of a noise spectrum analysis of the recording of the engine failure, which might have been helpful in identifying the cause of the fan blade failure.

1.3.3 Sequential damage
To identify the nature of an engine failure with a heavily damaged fan rotor, its damage has to be assessed. When the possibility of an ingested object is suspected, it is essential to filter sequential damage from primary damage caused by an ingested object. The size of the ingested object should be associated with leading edge distortions (cusps) and cascade features are indicative for sliced (soft) bodies.

Most of the obvious damage to the fan and fan inlet duct is the result of sequential damage. The propagation of such damage is difficult to reconstruct exactly. However, the fact is that when small blade fragments or blade tips separate they travel radially due to centrifugal forces and circumferentially as forced by their blade speed and shape of the inlet duct. Because of the

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[1] Besides to learn from accidents and incidents in accordance with ICAO, investigations carried out by the Dutch Safety Board may also serve to obviate social concern within the Dutch society caused by occurrences as embodied in Dutch law (Rijkswet Onderzoeksraad voor veiligheid, memorie van toelichting).

aerodynamic force on the parts they initially spiral forward until they are sucked back into the engine. In this process they gouge out acoustic panels and the attachments bolts they may find on their way. Once hitting the fan themselves they cause secondary damage to the fan which may release other parts to contribute to more damage. Depending on dynamics separated parts may either penetrate (and exit) the fan casing or cowling, or blow rearward out of the fan exhaust or into the core engine, thereby generating more internal sequential engine damage. These kinds of failures are usually accompanied by explosive sounds and blow-pipe flames out of the engine exhaust or sometimes out of the inlet duct.

1.3.4 Visual inspection and damage description

A first rough visual inspection of the engine took place approximately 14 hours after the event occurred with the engine still mounted at the aircraft which was still parked outside. During this inspection no signs of organic remains or a typical bird ingestion smell were observed. A more thorough visual inspection was carried out about two weeks later (July 13, 2005) after the engine had been removed from the aircraft and stored in an engine cell. No evidence of blood, feathers or obvious organic disposal were found.

The fan of a General Electric CF6-50 engine consists of 38 blades. Generally, the blade labelled as blade 1 was broken off. All other blades were severely damaged, see figure 1.
The fan blades starting from number 2 anti-clockwise through blade 28 were found in a shingled condition[2]. The blades 29 through 38 were not in a shingled condition but did have evidence of shingling damage. The concave side of blade 38, blade 1 (failed) and blade 2 do not show shingling damage, see also appendix A page 19 table 1 of the metallurgical report. Also no print of the hard face[3] of the mid-span shroud from blade 1 was found on blade 2.

The leading edges of the broken fan blade and its neighbouring blades were examined to identify possible ingested objects. The broken blade and its neighbour #38 show cusps, see figure 3. According to an engine accident specialist (see 1.3.7) hard objects may create cusps, but only under low engine speed (RPM) conditions at random locations on the fan rotor.

1.3.5 Boroscope inspection

The boroscope inspection was conducted on the 5th of July (six days after the event occurred) by General Electric On Wing Support on request of the insurance company of the operator. The boroscope inspection report mentions that the boroscope inspection was carried out due to FOD. Except the description of the expected secondary damage to the internal engine and fan rotor, the report does not reveal significant findings.
The Safety Board supervised the inspection and together with investigators from Airbus and representatives from Fly Air and General Electric the opportunity was taken to have a better look at the engine. The acoustic lining in front of the fan rotor was completely missing and fan blade debris was found embedded in the fan inlet duct. The engine inlet flange was distorted at approximately 10 o’ çlock position (forward looking aft). A piece of the flange appeared to be missing. In that area there was a hole in the fan cowling.

1.3.6 Ultraviolet light inspection

The ultra-light inspection concentrated on all the fan blades, particularly in the area of the broken blade #1 and its neighbouring blades. Furthermore, the fan inlet duct and the spinner cone were examined.

All over the fan rotor and the spinner cone tiny insect spots were visible by the ultraviolet light. The general appearance of insect marks was consistent for the entire fan rotor and spinner cone. No remarkable spots were observed in the area of the broken fan blade.
On fan blade #13 an isolated spot (approximately 2 or 3 centimetres diameter) was found on the fan blade tip. It merely was a round splash rather than a wipe and its illumination in the ultraviolet light was seemed to be lesser than the insect spots. During the black light inspection no conclusion of the nature of this spot could be made. The fan inlet duct visual inspection did not reveal any signs of organic disposal or spots.

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[2] Shingling: this is the condition of the mid-span shroud overlapping the shroud of an adjacent blade instead of abutting at the contact surfaces.

[3] Hard face: contact faces of a mid-span shroud.

1.3.7 Metallurgical Failure analysis
The Safety Board requested the National Aerospace Laboratory NLR to investigate the (metallurgical) root cause of the fan blade failure.

The following parts were sent to the NLR for investigation:
- the broken blade - labelled as blade 1, and neighbouring blades 2, 38 and 37
- blades 13 when necessary for additional tip damage and / or observed spot examination
- debris found in the engine and on the runway
- a piece of fan cowling damaged by an exiting part (figure 2).

The NLR concludes that no pre-existing flaws or other defects in the blade were found. Overall, fan blade 1 was in a proper condition. No signs of fatigue could be identified. However, it is mentioned that not all fracture surfaces could be examined due to damage. Furthermore, a considerable length of the leading edge of the broken fan blade, which might have included an initiation point of the fracture as a result of possible pre-existing damage (e.g. a notch), was not found.

The fan blade failed due to overload either by foreign object damage (FOD) or domestic object damage[4] (DOD). Additionally, as the ingested object could not be identified the NLR considers it to be more likely it was a hard object. It concludes that it is quite possible that hard objects do not leave behind recognizable traces. Furthermore, if it would have been a bird, then in view of the NLR it should have been a large bird which should leave traces.

It could not be established what material had penetrated and exited the fan cowling.
The full report from the NLR is attached under appendix A.

1.3.8 Photographic analysis
A gas turbine accident investigator course instructor was consulted by showing him pictures of the damaged fan rotor and the broken and adjacent blades in particular. He points at the cusps of the broken blade and the neighbouring blade (38) in a cascaded fashion. His analysis reveals that a single soft body object weighing less than a pound hit the fan rotor, the size comparable to that of a pigeon. Pre-existing notches in the leading edge may allow that even cusps caused by a small bird cause a fan blade to fracture. Evidence for this may be seen provided the original fracture is still intact.

Cusps may create internal stresses in the leading edges of the fan blade material (membrane stress) or intercept a significant change in body sections like the mid-span shroud areas (step increased stress), which may cause little cracks. Following other deformations of the blade it can immediately cause the blade to fracture. This is much more common for soft bodies such as large birds (more than 2 lbs).

More detailed information is presented in appendix B.

1.3.9 Other instances
The Dutch Safety Board reviewed several uncontained engine failure events that have been investigated worldwide over the past decades. Two of these events are briefly discussed in this paragraph since they add perspective to the investigation into the Fly Air case.

The first example also relates to failure of a fan blade in the mid-span shroud area and illustrates that disposal of detailed factual information, such as recovered fan blade remnants, can be crucial to determine the exact cause of the blade failure.
The second example illustrates that in depth investigation might be required to identify the substance of the ingested object and to distinguish Domestic Object Damage (DOD) from Foreign Object damage (FOD).
An instance that occurred on March 22 1999 shows similar fan blade failure damage. An Australian Boeing 767 suffered an in-flight engine failure (Pratt & Whitney JT9D) of one of its engines during climb of a domestic flight. It was accompanied by a loud bang, flashes and sparks and vibration. It appeared that one fan blade had fractured as a result of fatigue crack growth. Traces of mineral debris were detected at the crack origin, indicating that the foreign object damage was the result of stone ingestion. Fatigue crack growth, from a crack depth of 1.5 mm, probably occurred over

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[4] Domestic object damage: damage caused by an object (part) from the engine itself which came loose and was ingested.

about 35 flight cycles. The blade had no material abnormalities at the fracture site. No evidence of a bird strike was found.

During the initial climb of a DC-10 in December 1997 the crew experienced a malfunction of the tail mounted engine. The General Electric CF6-50 engine was shut down and the aircraft returned. The fan blades were heavily damaged and one blade broke off just below the mid-span shrouds. Black light inspection did not reveal bird remains on the fan blades and no fan blade material defects were found. Consequently, it was concluded that the fan blades failed by a heavy impact, most likely from the flexible bell mouth between the aircraft structure and tail engine. However, additional investigation after further engine teardown revealed little feathers of a sea eagle in an oil cooler. After all, it was concluded that the failure probably was the result of a bird ingestion.

2 ANALYSIS

2.1 THE BROKEN FAN BLADE

The metallurgical investigation of the NLR revealed that the broken fan blade was in a proper condition. In the NLR report it is concluded that it failed due to overload, either caused by Foreign Object Damage (FOD) or Domestic Object Damage (DOD).

In this event DOD could only originate from the missing acoustic lining in front of the fan rotor. However, most of the obvious damage to the fan and fan inlet duct usually is the result of sequential damage caused by the dynamics with these failures. It often includes badly damaged or missing acoustic liners. Furthermore, it cannot explain the cascaded cusps which are an indication of soft body impact. The Safety Board concludes that the event was not caused by Domestic Object Damage.

It could not be established what material had penetrated and exited the fan cowling.

2.2 FAILURE OF THE BLADE

Unfortunately not all fractures could be examined due to damage of the fracture surfaces and missing leading edge material of the broken fan blade, see also 2.3. This might explain why investigation could not identify what metallurgical scenario led to the fracture by overload.

From the absence of shingling damage to the concave side of blade 38, blade 1 and 2 and the absence of the mid-span shroud print on blade 2 it can be derived that fan blade 1 fractured before the other blades deformed and shingled. Combined with the cusps distortion on blade 1 and 38 it can be concluded that the impact energy started on blade 1 which led to the instant fan blade failure.

2.3 FOREIGN OBJECT DAMAGE (FOD)

General
The boroscope inspection report written by General Electric On Wing Support did not reveal findings to the cause of the engine failure, except that it was Foreign Object Damage (FOD). However, it did not explain how it has come to the conclusion of FOD.
Unfortunately, CVR information was not available for a noise spectrum analysis.

The evening conditions, the workload during take-off immediately followed by an engine failure and the rejected take-off do not support a reliable observation of the crew. Nor the initial report of the crew to Air Traffic Control of the" animal" observation, nor the denial of the "animal" by one of the pilots in a later stage is of any support to the identification of the foreign object.

No conclusion could be made of the nature of the spot found on blade 13. However, based on its shape and illumination during the black light inspection the Safety Board does not believe there would be a relation with this incident.

The investigation did not reveal obvious evidence of blood, feathers or organic disposal or the typical smell for bird ingestions. It is mentioned that the time between the event and inspections were too long and the overall conditions might have affected the investigation results unfavourably. Further tear down of the engine might have revealed unnoticed object evidence. The Safety Board did not choose to tear down the engine. It is concluded that the quality of the field investigation cannot exclude that this evidence was missed.

Metallurgical investigation
The NLR concluded that based upon its metallurgical examination the ingested object could not be identified. Nevertheless, the NLR considers it to be more likely it was a hard object that was ingested. In its reasoning the NLR assumes it is unlikely that large birds should not have left behind organic traces. Furthermore, the absence of traces suggests it is more likely to be hard body than soft body, because it is quite possible that hard bodies do not leave behind traces.

Primary and sequential damage
When the possibility of an ingested object is suspected, it is essential to filter sequential damage from primary damage caused by an ingested object. In this event the object was ingested during high engine RPM condition (take-off thrust). The broken fan blade and its adjacent blade number 38 show cusps in a cascaded manner. Cusps may create internal stresses in the fan blade which may cause little cracks resulting into a blade fracture.

According to the gas turbine accident expert hard objects may create cusps, but only under low engine speed (RPM) conditions at random locations (not cascaded) on the fan rotor. Cascaded cusps are typical for soft body impact damage. Based upon the fan blade leading edge damage, the gas turbine accident investigation expert analysed that the ingested object was estimated to be a small bird in this event. Pre-existing notches in the leading edge may allow that even cusps caused by a small bird cause a fan blade to fracture. A possible fracture initiation point starting from such a notch could not be identified due to missing leading edge material of the broken fan blade.

The Safety Board took notice of the opinions of the NLR and of the gas turbine accident expert. Their opinions have been included. However, the Board believes that in light of this investigation it is irrelevant whether the FOD was caused by a soft (including bird) or hard body object.

2.4 Fly Air safety level

The cause of the broken fan blade was an autonomous factor. Consequently, the Fly Air engine failure had no relation to the questioned safety level of the operator in the media and the intensified supervision by the Civil Aviation Authorities of The Netherlands at that time.

3 CONCLUSIONS

The uncontained engine failure was caused by the impact of a foreign object during the take-off roll. The substance of the object could not be determined with reasonable certainty.

No recommendations were made.

APPENDIX A. FAILURE ANALYSIS OF BROKEN CF6-50 FAN BLADE: NLR-CR-2005-475-RE

Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Executive summary

Fly Air uncontained engine failure

Failure analysis of broken CF6-50 fan blade

Revised Edition

Problem area
A Fly Air aircraft had to abort take-off at Schiphol Airport because of an uncontained engine failure.

Description
Standard methods - such as optical microscopy, hardness measurements, Scanning Electron Microscopy (SEM) and Energy Dispersive analysis of X-rays (EDX) - were applied to investigate the cause of the failure.

Results and conclusions
The broken blade did not exhibit defects. The fracture mode was overload failure (and not e.g. fatigue crack initiation and propagation) but the reservation has to be made that consequential damage did not permit the investigation of all fracture surfaces.
The root cause of the fan blade failure was very probably Foreign or Domestic Object Damage. The nature of the Object could not be determined.

Report no.
NLR-CR-2005-475-RE

Author(s)
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Classification report
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Knowledge area(s)
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Descriptor(s)
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foreign object damage

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NLR-CR-2005-475-RE

Fly Air uncontained engine failure

Failure analysis of broken CF6-50 fan blade
Revised Edition

H.J. Kolkman

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Summary

An investigation of a broken fan blade did not reveal deficiencies in the blade. As far as consequential damage permitted the investigation of the original fracture surfaces, the fracture mode found was always overload failure (and not e.g. fatigue crack initiation and propagation). The most probable root cause of the incident is Foreign or Domestic Object Damage by a hard object. The nature of this object could not be determined.

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List of acronyms and abbreviations

DOD	:	Domestic Object Damage
EDX	:	Energy Dispersive analysis of X-rays
FAR	:	Federal Aviation Regulation
FOD	:	Foreign Object Damage
HV	:	Vickers Hardness
LE	:	Leading Edge
OM	:	Optical Microscopy
SEM	:	Scanning Electron Microscope
TE	:	Trailing Edge

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1 Introduction

On 29 June 2005 an Airbus A300 aircraft of Fly Air had to reject its take-off at Schiphol airport because of problems with the left hand engine. The main observations after the incident were that a fan blade of this GE CF6-50 engine had broken (Fig. 1) and that the failure was uncontained (Fig. 2). All other fan blades were damaged, an acoustic panel had disappeared, etc.
The Dutch Safety Board requested the NLR to determine the root cause of the fan blade failure.

A number of material science expressions and the geometry in a fan are elucidated in appendix A.

2 Description of the components investigated

The fan of a CF6-50 engine consists of 38 blades, made of Ti-6Al-4V. In addition to the broken blade - labelled as no. 1 (see Fig. 1) – the following was received for investigation:

- Blades 2 and 38 (the neighbours of the broken blade, see Fig. 1).
- Blades 13 and 37.
- Tens of pieces of debris, partly found in the engine and partly on the runway. With respect to the debris found on the runway, it is not certain that all debris originated from the Fly Air engine.

The aforementioned debris included:

- Debris originating from the fan blades. This subject is discussed in § 4.3.
- A piece that had almost separated from the fan cowling (Fig. 2). After the incident, this piece was broken out by the Dutch Safety Board. Investigation of this piece is discussed in § 5.2.
- Other debris, not investigated by the NLR.

3 Experimental methods

The work started with macroscopic examination and photographing. Thereby fracture surfaces were selected for investigation with SEM [1] (Scanning Electron Microscopy). The limited space in the SEM required the cutting up of the inner airfoil and the pair of shrouds [2] (see Fig. 3 for definitions). Prior to the SEM investigation the fracture surfaces were cleaned ultrasonically, first in a solution of the detergent “Dubro” and next in alcohol.
Chemical compositions of a.o. deposits on fracture surfaces as well as “smear marks” on the surfaces of the blade fragments were determined by means of EDX (Energy Dispersive analysis of X-rays) in the SEM.
After SEM investigation, cross-sections were made and investigated in the etched condition with Optical Microscopy (OM). The etchant was 2 ml HF, 8 ml HNO_3 and 90 ml H_20.
Rockwell C macro hardness [1] values were measured in a cross-section (perpendicular to the blade length direction) under the fracture surface of the inner airfoil (Fig. 3). Vickers micro-hardness [1] values in a superficial layer were determined with 50 g load.

4 Macroscopic investigation

4.1 General

All blades were damaged; one blade was broken (Fig. 1). According to information obtained from the Dutch Safety Board, the blades labelled 2 - 28 were shingled (i.e. the midspan shrouds of neighbouring blades were shifted over each other) whereas the blades 1 and 29-38 were not. Obvious indications of a bird strike such as little feathers, blood, or organic residue were not found during the investigation. An overview of a number of macroscopic investigations is presented in table 1.

4.2 Main fragments of the broken blade

The main remnants of the broken blade are shown in figure 3, namely a part of the blade that remained in the rotor and a part containing the “midspan shrouds”. Clearly, pieces of material are missing at A and B. Knowing that the total length of the blade – measured in the way indicated in figure 3 – is about 675 mm, it is clear that the part of the blade between C-C and the tip – the so-called outer airfoil - is missing as well. The debris did not contain single pieces of metal that would fill A, B or the space between C-C and the tip completely. In other words, the

[1] See Appendix
[2] Each blade has two midspan shrouds, one at the convex and one at the concave side.

missing segments at A, B and C-C had probably broken into many small pieces. It is not certain that all small pieces were recovered.

4.3 Debris

Generally speaking, it was unknown whether debris originated from the broken blade or the other damaged blades. An exception was the debris originating from the tip of the broken blade. The blade tip can be recognized since there is a step in blade thickness at the concave side (Fig. 4). The debris contained eight pieces of metal originating from blade tips; six of them are shown in Fig. 5). One of these pieces (in the upper right corner of Fig. 5) contained a Leading Edge (indicated as LE) as could be judged from its limited thickness and the presence of the beginning/end of the aforementioned thickness step. This piece might originate from the broken as well as from other blades, since some blades missed a piece of the tip at the LE (e.g. blade 38 in Fig. 1). The other, thicker tip segments certainly originated from the broken blade since no pieces were missing from the central (thicker) tip portions of the other blades. It could not be determined how these pieces fit together. This is illustrated by one of the pieces in figure 5, which is shown at higher magnification and from both sides in figure 6. In the right hand figure a straight fracture surface (perpendicular to the tip) is seen. No tip fragment with a matching fracture surface was found. Probably this matching fracture surface was destroyed upon collisions.

In view of the blade length, pieces of metal were still missing between the blade tip and the midspan shroud (C-C in Fig. 3). Most – if not all – of these missing pieces were probably contained in the debris. The problem, however, was to determine whether a particular fragment originated from the broken blade (or from another blade) and if so, from what location.

Although the missing parts of the broken as well as the other damaged blades contain a considerable length of LE (Leading Edge) and TE (Trailing Edge), hardly any debris containing a part of a LE or TE was found (Fig. 7). This is since the thin LE’s and TE’s are easily damaged by collisions.

4.4 Tip rub

Generally speaking, tip rub is manifested by a lip of overhanging tip material at the convex side [1] and by grooves at the tip surface. Out of the blades investigated:

- Blade 2 and 38 (the neighbours of the broken blade) exhibited very local tip rub, apparently caused by particles stuck between the tip and the fan duct.
- Blade 13 exhibited severe and uniform tip rub.
- The tip fragments of the broken blade exhibited uniform and very severe tip rub. This is exemplified in figure 8.

  It is known that the tip fragment shown in figure 8 originates from the broken blade because of its size: no fragment of this size is missing from the other blades (see Fig. 1).

Two defect types are seen at the tip of the broken blade: tip rub (arrowed) and dents (labelled D). Such dents are also present for other blade tips and can be explained by debris that got stuck between the rotating blades and the duct.

4.5 Fracture surfaces

The fracture surfaces of the main fragments of the broken blade as well as all debris were macroscopically inspected. The following remarks apply:

- Many fracture surfaces were damaged by collisions, rub, etc.
- Many fracture surfaces exhibited overload failure
  Overload is immediate failure that occurs if the strength of a material is exceeded. Fracture surfaces produced by overload are characterised by dimples [1]. Components can fail by overload only and this situation is referred to here.
  (In addition, cracking of a component by another mechanism - e.g. fatigue cracking, stress corrosion cracking - is almost always followed by overload since ultimately the load bearing cross-section is decreased by the presence of the crack to such an extent that the stresses at the remaining load bearing area exceed the strength of the material).
- At many locations small areas with interference colours (blue, yellow, etc.) were present. This discoloration was frequently observed for very smooth fracture surfaces and hence was apparently caused by rub.
- In one of the pieces of debris a feature was seen that might be a “forging lap [1] ”; see figure 9.

In view of the macroscopic investigation, a number of fracture surfaces were selected for the SEM [2] investigation to be discussed in § 5 and the cross-sections in § 6.

4.6 Midspan shrouds

An overview of the observations is given in table 1. figure 10 exemplifies the shingling damage mentioned in this table.

5 SEM

5.1 Fractography

The fracture surfaces of the inner airfoil (see Fig. 3 for location) as well as of the straight fracture surface in the tip fragment shown in figure 6 exhibited equiaxed dimples [1], as is illustrated in figure 11 - figure 16. Dimples are characteristic for overload failure.
The fracture surfaces of the midspan shroud (both with the inner and outer airfoil, see Fig. 3) exhibited much damage. A part of these fracture surfaces were covered with a layer of foreign

material that exhibited so-called mud cracking [1] (see Fig. 17 and Fig. 18). These layers were analyzed with EDX as will be discussed in the next subsection.

5.2 Determination of chemical compositions

As reference, figure 19a shows the EDX spectrum of a location at the concave airfoil surface, close to the aforementioned parts of the fracture surfaces. The following peaks are seen:

- As expected: peaks of the blade material, namely titanium (Ti), aluminium (Al) and vanadium (V).
- Carbon and oxygen
  These peaks originate from organic material. In this respect it should be remarked that hydrogen cannot be detected by means of EDX. The presence of some deposits of organic material is in the gas path of jet engines is rather normal.
- Small peaks of silicon (Si) and iron (Fe).

As exemplified in figure 19b and as compared with figure 19a, the EDX spectra of the aforementioned layers in figure 17 and figure 18 exhibit higher Si and especially Fe peaks and in addition to that nickel (Ni) and chromium (Cr) peaks. It should be realized that the electron beam penetrates a certain distance into the material and reaches the blade material through the thin layer, so that the spectrum in figure 19b is a kind of composite [1] of the spectrum of the Ti-6Al-4V blade material and the spectrum of the layer. Hence it was decided to make a cross-section through a fracture surface with a layer on it, so that the electron beam can be limited to the layer (and the penetration depth of the electron beam is completely contained in the layer [1]). This is one of the three cross-sections to be discussed in § 6.

It is likely that the upper part of blade 1 (i.e. the outer airfoil plus the midspan shroud) broke off and was subsequently chopped into many pieces by the rotating fan. It is also likely that if FOD or DOD was involved, the blade was hit at the concave airfoil (in view of the blade rotation direction [1]) near the LE. Hence EDX analyses were also performed at the concave airfoil surface near P in figure 3. However, no traces that might have left behind by an impacting particle were found near P.

The location in the fan cowling shown in figure 2 was apparently hit from the inside and penetrated by some particle. As mentioned in § 2, the encircled piece (that had almost separated from the fan cowling) was broken out by the Dutch Safety Board. It was investigated in an attempt to determine the nature of the aforementioned particle. EDX analysis revealed only elements of the fan cowling itself (mainly aluminium) and paint.
The surfaces of all pieces of debris were investigated macroscopically. Three pieces were selected for EDX analyses since they were thought to exhibit “smear marks”. Again, EDX analyses revealed mainly aluminium, i.e. material of the fan cowling.

6 Cross-sections

Figure 20 exemplifies the microstructure in a cross-section through the inner airfoil (close to the fracture surface seen in Fig. 3). The microstructure is normal for the heat treatment of the material, namely: 1300 °F for 2 hrs. anneal + 1020 °F for 2 hrs. stress relieve (Ref. 1).
The following hardness values [1] were measured in the same cross-section:

R_C hardness measurement results	Average	Standard deviation
36.8; 36.1; 36.2	36.4	± 0.3

This hardness is normal for the proper heat treatment condition of the material (Ref. 2).

Figure 21 is a cross-section through a piece of debris (of unknown location) namely through the feature arrowed in figure 9. Clearly no "forging lap[1] " but a crack is involved, since there are sharp crack tips, since the irregular fracture surfaces match and since there is no oxide layer.

Figure 22 shows an overview and details of the cross-section through the layer at the fracture surface seen in figure 18. Figure 22a shows that the edges of the original fracture surface were rounded off, probably by rubbing or collisions. The original fracture surface is still present under the layer that is clearly seen in figure 22a as a white area, hardly without visible microstructure [3]. The latter – as well as the gap between the layer and the blade material -is seen more clearly in the detail in figure 22b. Figure 22b also shows features that are characteristic for *very high deformation rates*, namely a row of voids as predecessor of a crack (labelled as VV) and an adiabatic shear band (labelled as AA). An adiabatic shear band is also seen in figure 22c. In adiabatic shear bands the high deformation rate is that high that the associated temperature rise results in local annealing of the material. Consequences are:

- The adiabatic shear band is seen as a band without much microstructural features, i.e. as a white band.
  The layer on the fracture surface in figure 22 is also white and rather featureless, but it is certainly not an adiabatic shear band in view of its chemical composition differing from the blade material and the gap between the layer and the blade material.
- Since the adiabatic shear band is annealed (and hence soft) further deformation becomes concentrated in the adiabatic shear band.

[3] This is not to say that the layer material is amorphous; the etchant applied to the blade material might be unsuitable to reveal the microstructure of the layer material.

Finally, figure 22d shows cracks (labelled as SS) just under the gap between layer and the blade material, that were probably caused by shock waves, again a phenomenon that is associated with high deformation rates.

It might be wondered whether the layer (as remnant of an impacting particle) caused the high deformation rate phenomena or whether the fracture surface - after it had been formed for some reason – became covered with the layer. In the first case it might be expected that the layer has a high hardness, since the hardness is increased by deformation. Vickers micro-hardness [1] measurements gave the following results:

Location	HV micro-hardness measurement (50 g load)	Average	Standard deviation
blade	345; 353, 353, 358, 362	354	± 6
layer	391; 407; 407; 412; 435	410	± 14

It is seen that the layer is considerably harder than the blade material. In other words: the blade material and the layer material are different materials or the layer was heavily deformed (e.g. by impact). EDX was applied to differentiate between these possibilities: Figure 23 exemplifies an EDX analysis of the white layer. This is more accurate than the EDX analysis in figure 19b, since there is less disturbance by the blade material and since polished (i.e. smooth) cross-sections give more accurate EDX analyses than measurements on a relatively rough surface. The results of three EDX analyses are given in the table below. Spectrum 3, 5 and 6 refer to measurements made at three different locations.

Measurements	Ti	Cr	Fe	Ni	Mo
Spectrum 3	2.7	14.4	57.5	24.2	1.2
Spectrum 5	2.3	14.4	57.1	25.0	1.1
Spectrum 6	2.4	15.3	57.8	24.1	-
Average ± standard deviation	2.5 ± 0.2	14.7 ± 0.5	57.5 ± 0.3	24.4 ± 0.5	1.2 ± 0.1
A-286 steel [2]					
Min –max	1.90 -2.35	13.50 -16.00	balance	24.00 - 27.00	1.00 - 1.50

It is seen that the chemical composition of the layer corresponds to the chemical composition of A-286 steel, an austenitic steel with many applications in jet engines. The acoustic panels in the outer flow path just forward of the fan blades are held in position by bolts of A286 material (Ref. 1). Hence it is likely that the A286 material found originates from a collision of the fracture surface under consideration with such a bolt. In other words, it is likely that sequential damage is involved.

7 Discussion

7.1 General

It is very likely that for some reason – to be discussed in the following subsections - the upper part of blade 1 (i.e. the outer airfoil plus the midspan shroud) broke off and was subsequently chopped into many pieces by the rotating fan. Generally speaking, evidence was possibly lost because of sequential damage. For example, the original fracture surfaces might have been damaged by the aforementioned chopping and collisions with the fan cowling, etc. It should be kept in mind, however, that upon a fracture always two fracture surfaces (being mirror images of each other) are created. It is less likely that *both* fracture surfaces are destroyed by sequential damage. Nevertheless, this cannot be excluded and hence the possibility that both original fracture surfaces were destroyed should be kept in mind upon considering the next subsections.

7.2 Blade condition

The broken blade was in good condition: microstructure and hardness [1] were correct for the locations investigated (§ 6). The microstructure and hardness are the result of the heat treatment of the blade upon manufacturing. Since the entire blade was subjected to this heat treatment, it follows that the microstructure and hardness were correct for the entire blade.
No internal defects – such as forging laps [1] (Fig. 9 and Fig. 21) – were found for the locations investigated. This does not exclude the presence of such defects elsewhere, but anyway internal defects – if present – were not associated with the blade failure.

7.3 Failure mode

All fracture surfaces investigated (§ 5.1) exhibited *overload failure* or were damaged to such an extent that determination of the fracture mode was impossible.
Overload is characterised by the presence of so-called dimples [1]. The dimples observed (exemplified in Fig. 12, Fig. 14 and Fig. 16) are equiaxed. This is characteristic for tensile overload or overload in bending (in contrast, elongated dimples are characteristic for shear [1]).
The crack propagation cannot be deduced from equiaxed dimples. The principal stress is perpendicular to fracture surface, i.e. in the length direction of the blade. During take off, the high centrifugal forces introduce a high tensile stress in this length direction. Of course, the blades should be able to withstand this stress. However, impact of the blade by a Foreign or Domestic Object or sudden impedance of the motion of the rotating blade by a particle that became stuck in between the blade tip and the duct (as will be discussed below), will cause bending of the blade. In both cases, this bending introduces extra compressive stresses near the convex side and extra tensile stresses near the concave side [2]. The latter stress adds up to the already high stress introduced by the centrifugal force.

For the sake of clarity is mentioned here that fatigue crack initiation and propagation is characterised by phenomena such as circular or elliptical “beach marks” at low magnification and fatigue striations (many parallel lines; the distance between each line corresponding to a load cycle) at high magnifications. The crack propagation direction is perpendicular to these markings. Such phenomena were not observed at all during the present investigation.

Given the fact that no blade defects were found (§ 7.2), potential root causes for a fan blade failure are:

1. Midspan shroud failure
   In the past the NLR investigated midspan shrouds, from which a piece was broken off. In such a case, the increased freedom of blade movement would give rise to blade vibrations and hence might lead to fatigue failure of a fan blade.
   In the present investigation no midspan shroud with a missing piece (and no fatigue crack propagation in the blade) was observed (§ 4.6 and Tab. 1).
   The shingling and the damage of the hardfaces [4] mentioned in table 1 is probably consequential damage.
2. Tip rub
   The blades – including the broken one – exhibited tip rub (Tab. 1 and Fig. 8). Tip rub (i.e. wear because of contact of the blade tip and the duct [5]) is rather normal. The broken blade no. 1 had been subjected to severe tip rub (Fig. 8), but since this was also observed for (the unbroken) blade no. 13 (Tab. 1), this tip rub was very probably already present before the incident.
   A special case of tip rub arises if a particle becomes stuck between the tip and the duct (shroud). If the movement of a rotating blade is adversely affected in this way, it might crack. The dents observed near the tips of the unbroken blades (e.g. D in Fig. 1) indicate that particles became stuck between the blade tips and the duct. The particles involved were probably debris. However, this explanation cannot hold for the dents observed in the tip of the broken blade: if the dents in the broken blade (D in Fig. 8) are caused by particles stuck between the blade tip and the duct, this must have happened before the blade failure. Hence these particles cannot be debris, since there was no debris before the blade failure. Thus the dents in the broken blade were either caused by collisions after the blade failure or by a Foreign or Domestic Object that became stuck between blade tip and duct. Typically, such an Object is a hard Object, since a soft object will be deformed to accommodate the limited space between blade and duct. Recently, the NLR was involved in a (confidential) investigation in which a failed fan blade exhibited dents

[4] Hardfaces are the contact faces of the midspan shrouds. They are coated with a so-called hammer resistant coating.
[5] The duct (also called shroud) is the inner art of the fan casing, near the fan blades.

similar to the ones shown in figure 8. It was shown that the blade failure was due to a particle that became stuck between the blade tip and the duct. The evidence was the (metal) particle itself that was recovered after the incident.
In such a case FOD or DOD is concerned. Under the following points other FOD/DOD cases will be discussed. In these following cases the Object does not become stuck between blade tip and duct; the damage is caused by the impact energy of the object.

3. FOD or DOD caused by a soft object
   Foreign Objects can be soft (such as birds) or hard (metals, stones, etc.). There is no metallographic evidence for a soft body impact. Small birds (such as sparrows) do not damage the engine at all (Ref. 3). For a single bird impact, FAR bird-impact airworthiness requirements refer to a bird of at least 1.85 kg. One of the requirements is that impact by such a bird may not cause the engine to release hazardous fragments through the engine casing (see, however, Fig. 2). It is imaginable that the blade failure was due to a bird of such a weight, but in that case much more remnants of that bird might be expected.
4. FOD or DOD of a “hard ” object, followed by fatigue cracking
   FOD or DOD of a “hard ” object usually give rise to impact damage, e.g. in the form of a sharp dent, from which a fatigue crack starts to grow (e.g. Ref. 5 and Ref. 6). Such a fatigue crack was not found during the present investigation and there is no metallographic evidence for a hard body impact.
5. FOD or DOD of a “hard ” object, followed by overload
   FOD can give rise to an immediate overload failure (not preceded by fatigue crack initiation and propagation) provided that the energy of the impacting particle is high enough. Again, it can be remarked that there is no metallographic evidence for a hard body impact.

Out of the five possibilities mentioned, only the second and the fifth are likely. Hence this will be discussed in more detail in the next subsection.

7.4 FOD or DOD

In case of FOD or DOD it is often possible to determine the nature of the impacting particle by analyzing the smear marks left behind. In the present investigation, aluminum and A286 steel were found. Since both materials are normally present in the fan under consideration, it is likely that these materials were left behind upon collisions with A286 bolts, the fan cowling and the acoustic panels. Nevertheless, it cannot be excluded that some aluminum, A286 steel or Ti-6Al-4V part originating from another aircraft was “launched” by the nose wheel of the Fly Air aircraft and caused the FOD.

It is almost impossible to differentiate between e.g. Ti-6Al-4V or A286 debris originating from the Fly Air aircraft and from other aircraft (in other words: it is almost impossible to differentiate between FOD and DOD), since Ti-6Al-4V and A286 are very common in jet engines.
For instance, it is imaginable that a piece of Ti-6Al-4V metal was left behind on the runway by another aircraft, was ingested by the engine of the Fly Air aircraft, impacted on the fan blade (or became stuck between duct and blade tip) and thereby caused the blade failure. In such a case, EDX will not reveal smear marks, since the fan blade material is also Ti-6Al-4V.

Going into more detail with respect to A286 steel, it should be remarked that this material was found on a fracture surface (§§ 5.1, 5.2 and 6) and not in the form of smear marks. Hence the most likely possibility is that the blade failed firstly and that subsequently a fragment with the fracture surface under consideration hit an A286 bolt of the acoustic liner. It cannot be excluded, however, that the root cause is that blade no. 1 was hit by a loosened bolt of the missing acoustic panel (§ 1) or by an A286 component ingested by the engine.
Still another possibility is that a piece of concrete was “launched” by the nose wheel of the Fly Air aircraft, hit the fan blade under consideration and was bounced back. It is quite possible that in such a case the brittle concrete will not leave behind traces on the blade.

8 Conclusions

The following conclusions can be drawn:

1. It follows from the metallographic investigation that:
   a) The broken blade was in proper condition (§ 7.2).
   b) The fracture surfaces were not associated with pre-existing flaws or other defects in the broken blade.
   c) All fracture surfaces examined exhibited overload failure; no fatigue failure was found. This conclusion cannot be drawn with 100% certainty, since it should be realized that a number of fracture surface were damaged in such a way that fractographic examination was excluded.
2. In view of conclusion 1. the root cause of the blade failure is very probably Foreign or Domestic Object Damage.
3. In that case, the blade failure was caused by the impact energy of the Object or by the impedance of the motion of the rotating blade by a (hard) Object that became stuck between blade tip and fan duct.
4. The Object mentioned under 2. could not be identified, since it did not leave behind recognizable traces.

5. In view of conclusion 4. a bird strike is unlikely: in order to provide enough energy for a blade failure, a large bird should have been concerned. It is unlikely that such a large bird would not leave behind any traces.
6. In view of conclusion 4, FOD or DOD by a hard Object (e.g. a metal fragment left behind on the runway by another aircraft or a piece of concrete) is likely, since it is quite possible that a hard Object does not leave behind recognizable traces.
7. It was impossible to differentiate between FOD and DOD.

9 References

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Table 1 Macroscopic results

Blade (see Fig. 1)	1 (broken)	2	13	37	38
Serial Number	AMD 17202	2DAS 1480	AMD 17460	2DAS 07999	AMD 17444
Midspan shrouds: Shingling - convex side - concave side Contact surface* - convex side - concave side	 no no S S	 no no OK I	 yes (Fig. 10) yes I OK	 yes yes I, S I, S	 yes no S OK
Tip rub	uniform, severe (Fig. 8)	very local	uniform, severe	very local (Fig. 4)	very local
Animal residues	no	no	no	no	no

* I : interference colours (local)
S : local spallation of hardface
OK : no I, no S

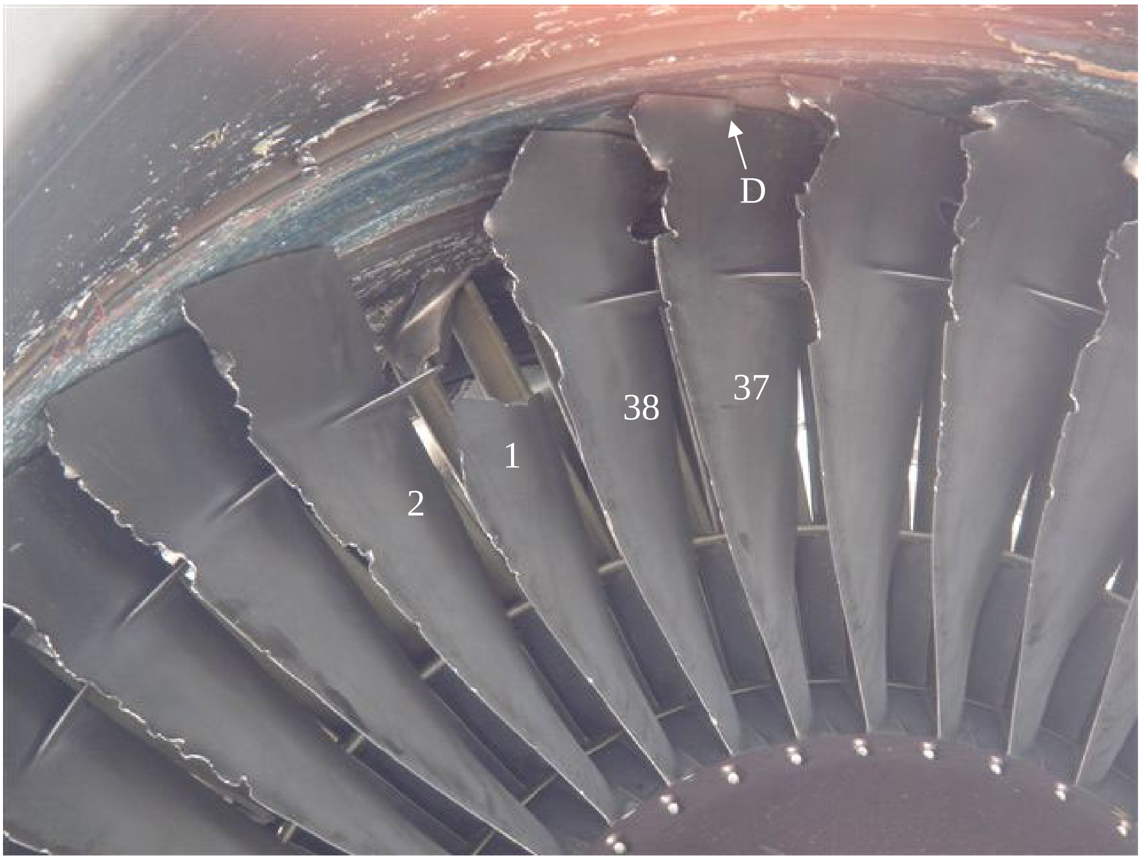


Fig. 1 *The broken fan blade – labelled 1 - and adjacent blades (courtesy of the Dutch Safety Board) seen from the engine inlet*

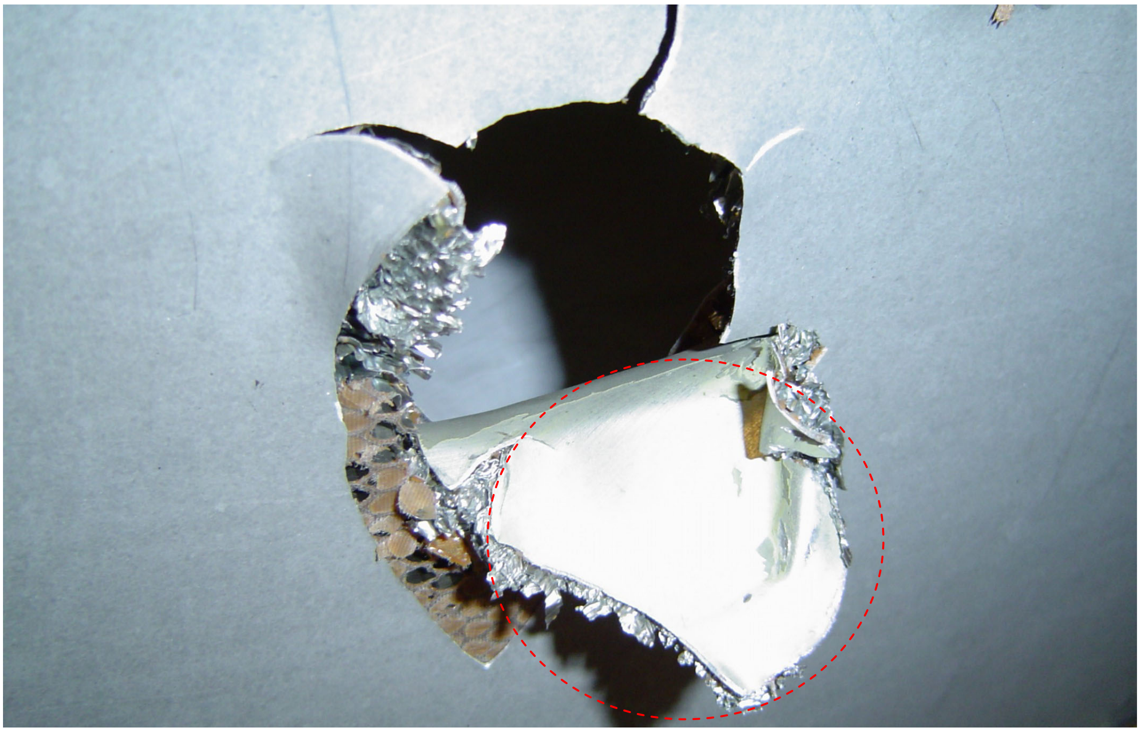


Fig. 2 *Hole in fan cowling as seen from outside (courtesy of the Dutch Safety Board). The encircled area was investigated with EDX*

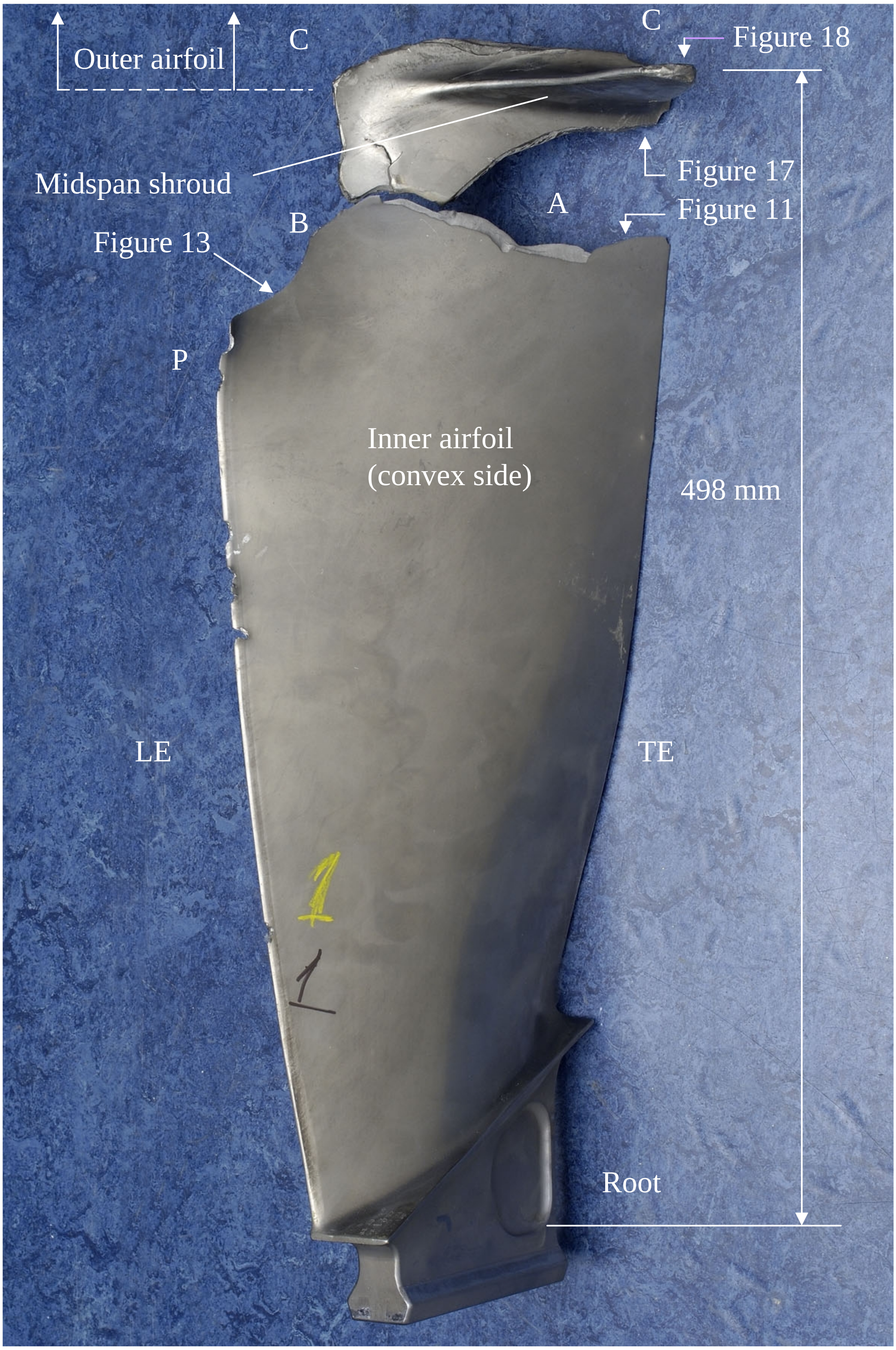


Fig. 3 Macroscopic view of the broken blade. The missing outer airfoil has a length of 168 mm

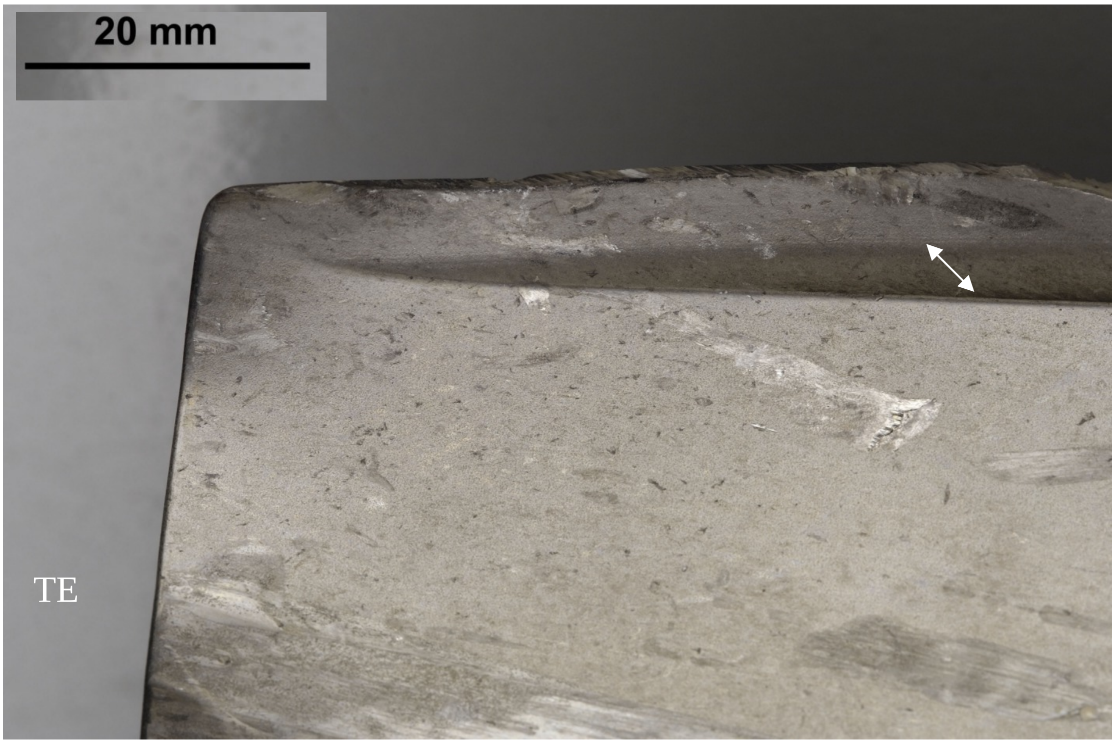


Fig. 4 *Part of the tip at the concave side of blade37. Note the absence of severe tip rub and the blade thickness step (arrowed) at the very tip*

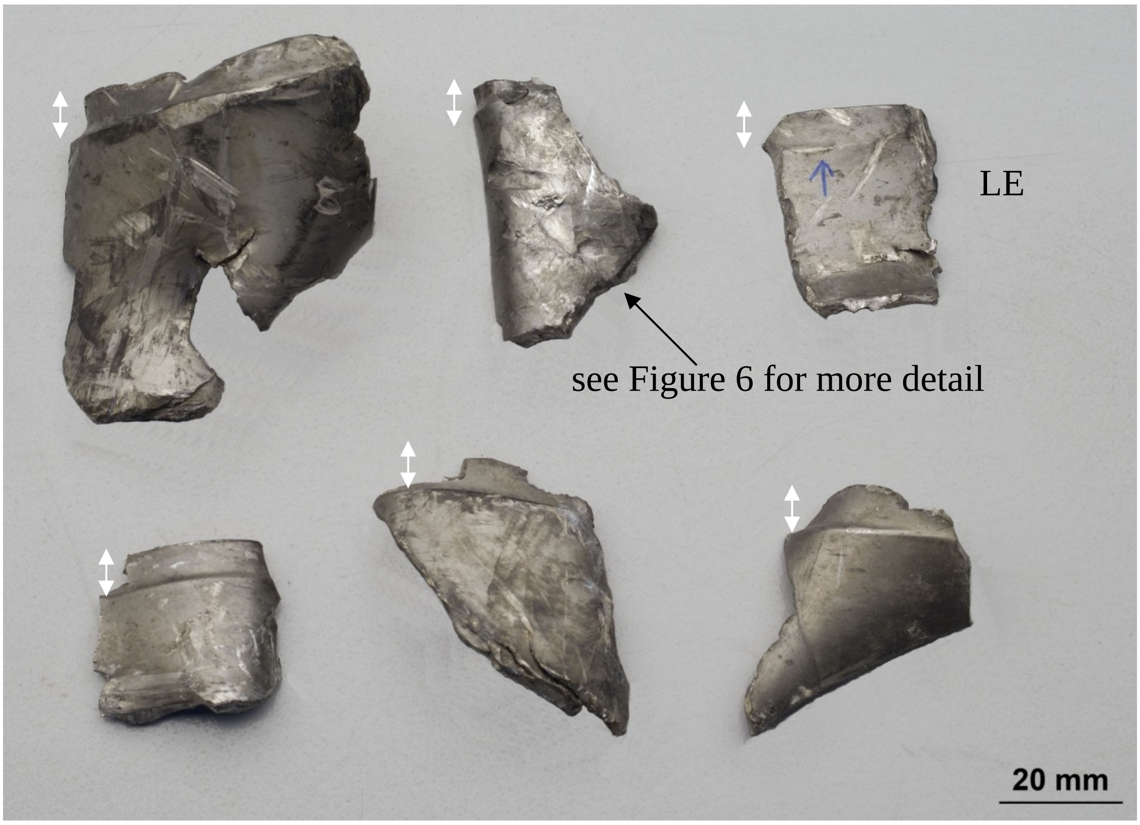


Fig. 5 *Fragments recognizable as tip segments because of the thickness jump (compare with Fig. 4). White arrows indicate the tip segment with reduced thickness (that is exemplified in Fig. 4)*

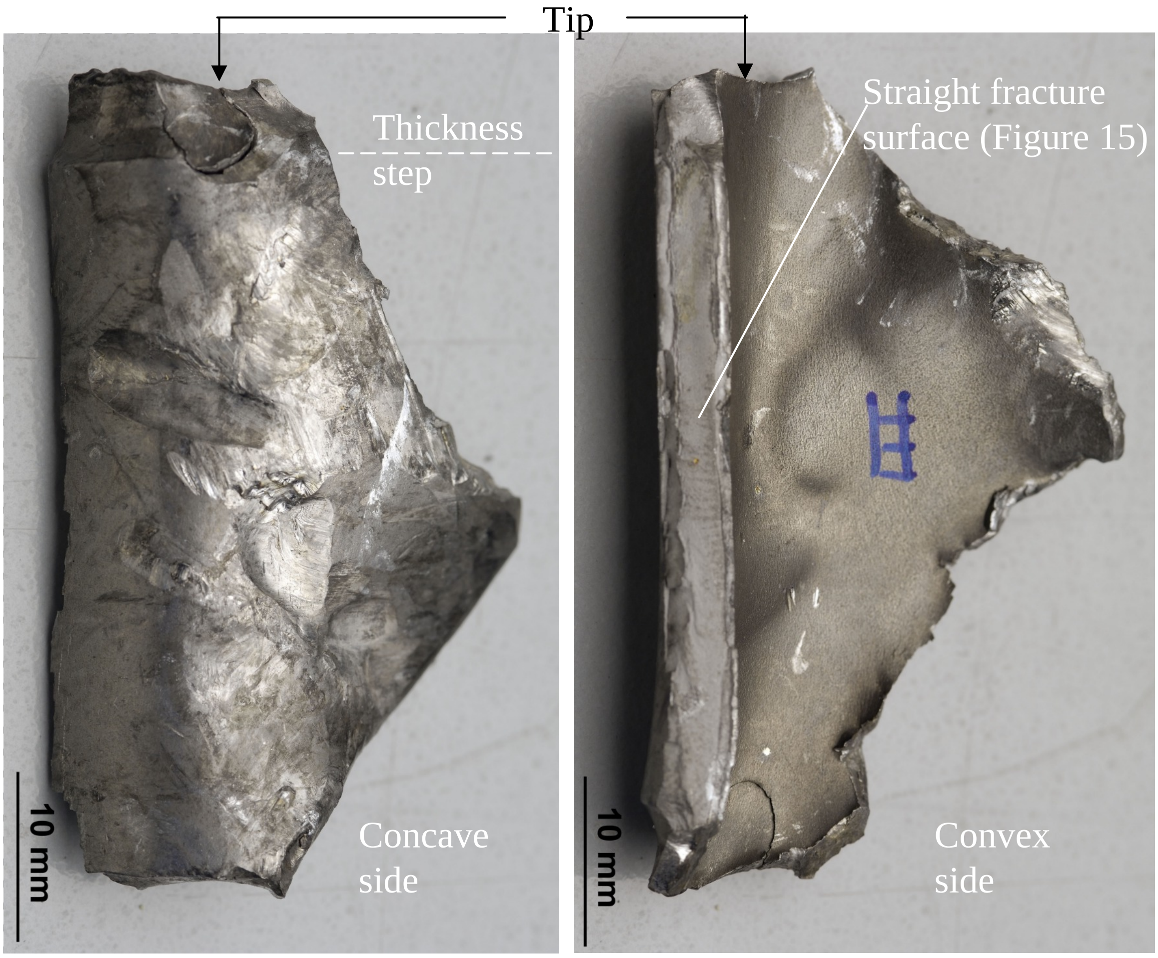


Fig. 6 *One of the tip fragments in figure 5 seen from both sides. Considering the curvature of the fragment, it might be thought that the left hand photograph shows the convex side. This curvature (found for all tip segments) is, however, a consequence of the severe deformation of the fragment: the thickness step in the left hand photograph proves that the concave side of the airfoil is involved*

Fig. 7 *The only two fragments exhibiting a recognizable LE or TE*

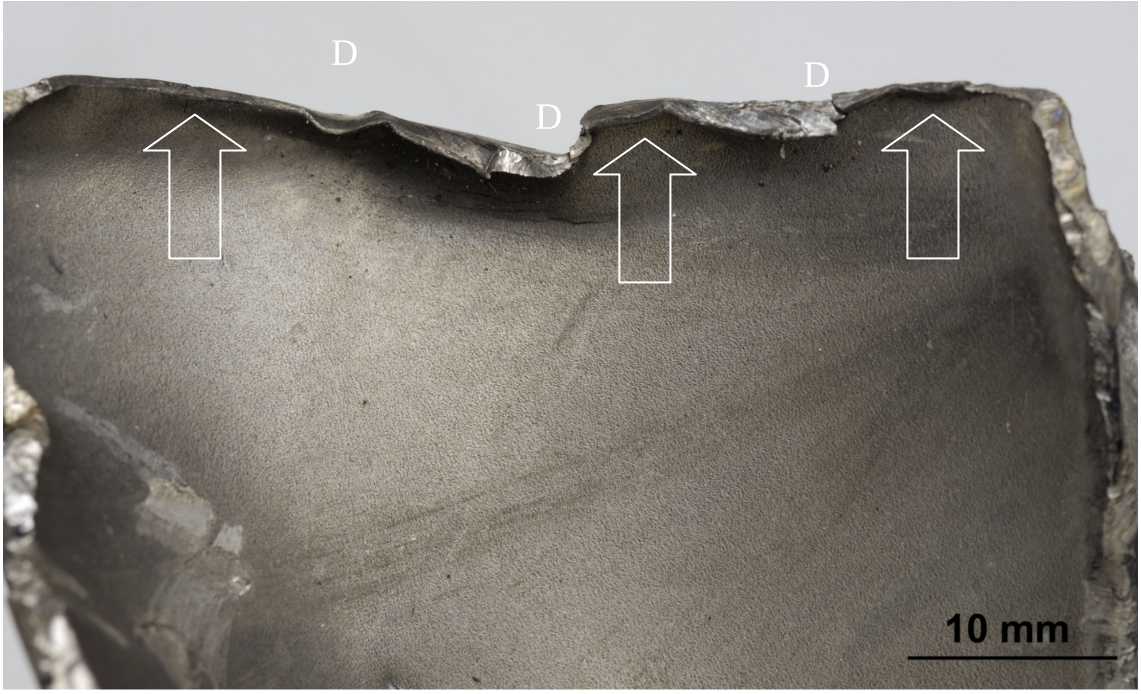


Fig. 8 *Tip fragment of broken blade exhibiting both tip rub (the arrowed overhanging lips) and dents D. For other blades dents like D are also present and can be explained by debris that got stuck between the rotating blades and the duct. However, for this fragment of the broken blade this would imply that debris was present before the blade broke and hence dents D were probably formed either by a Foreign or Domestic Object or by collisions after the blade failure*

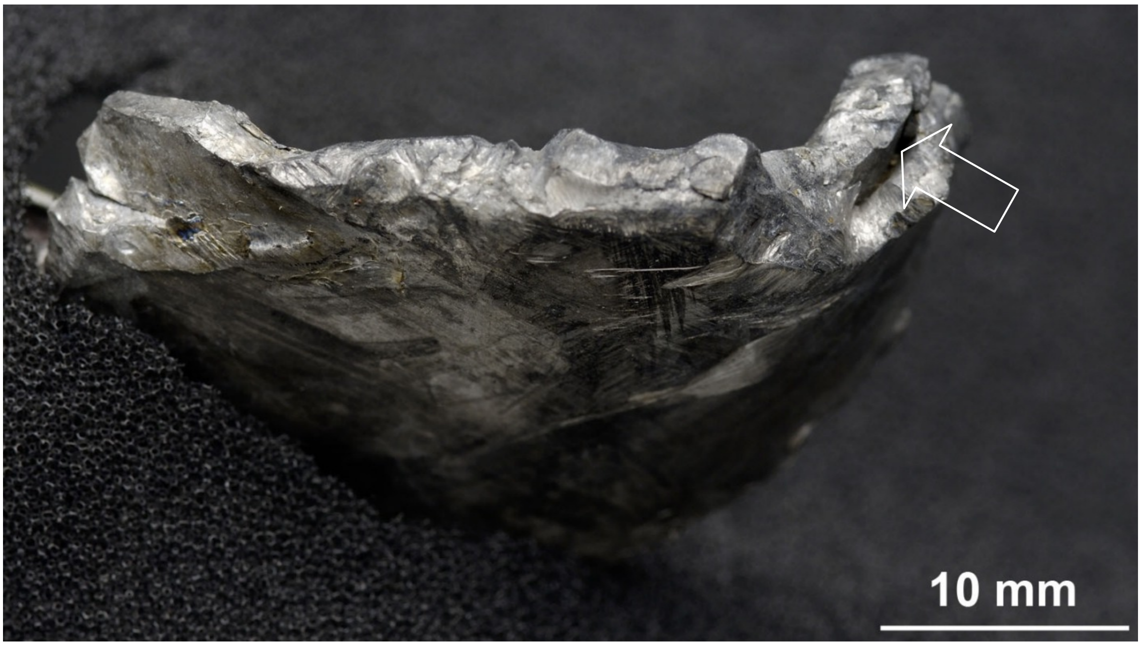


Fig. 9 Detail of fragment of debris. Note the arrowed feature

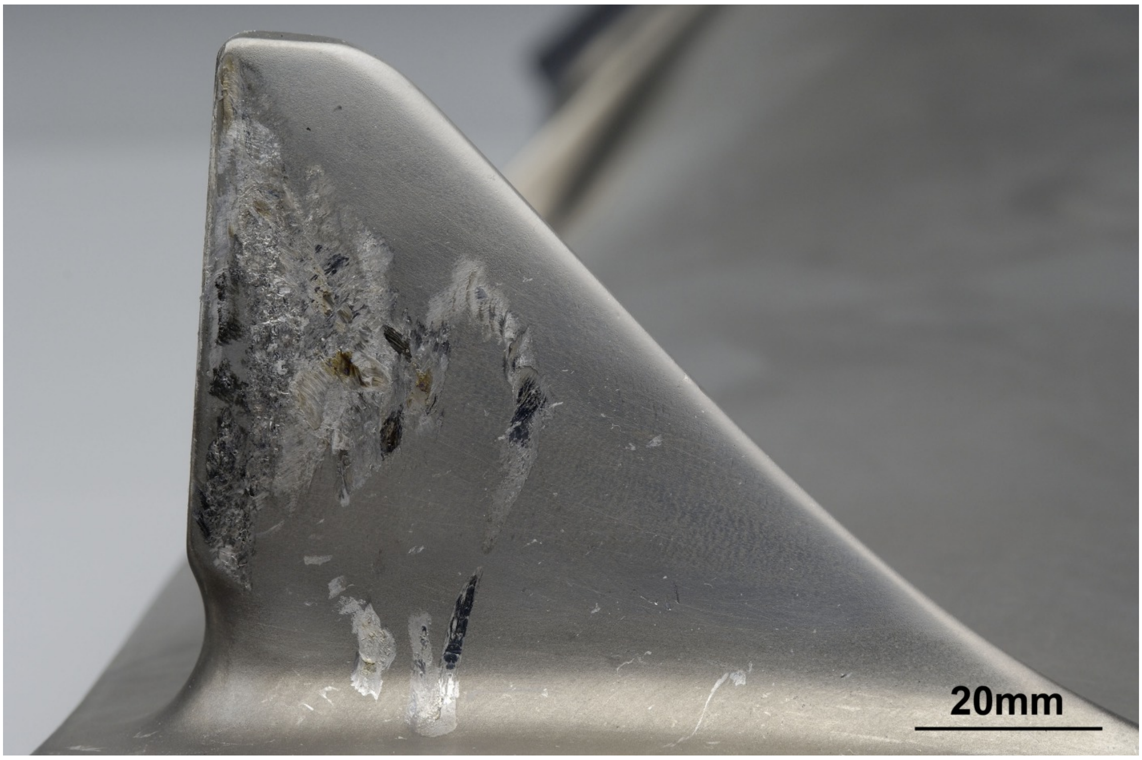


Fig. 10 Example of shingling damage of a midspan shroud (convex side of blade 13)

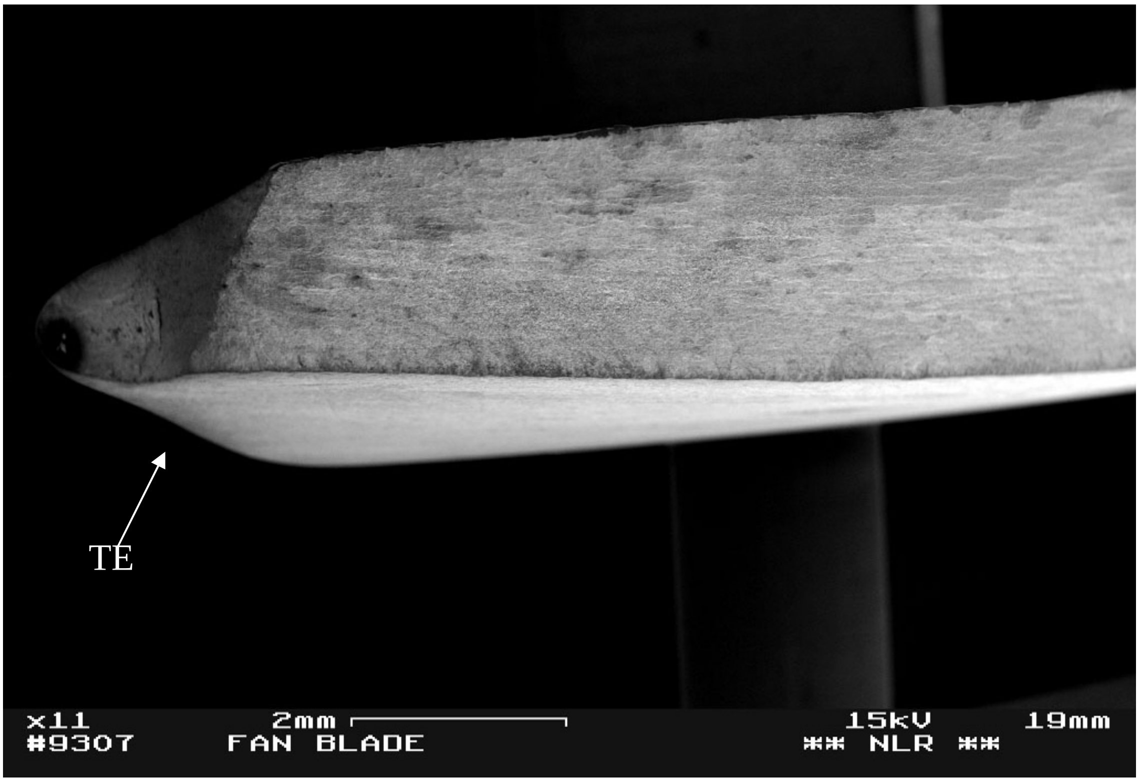


Fig. 11 Overview of fracture surface indicated in figure 3 (SEM)

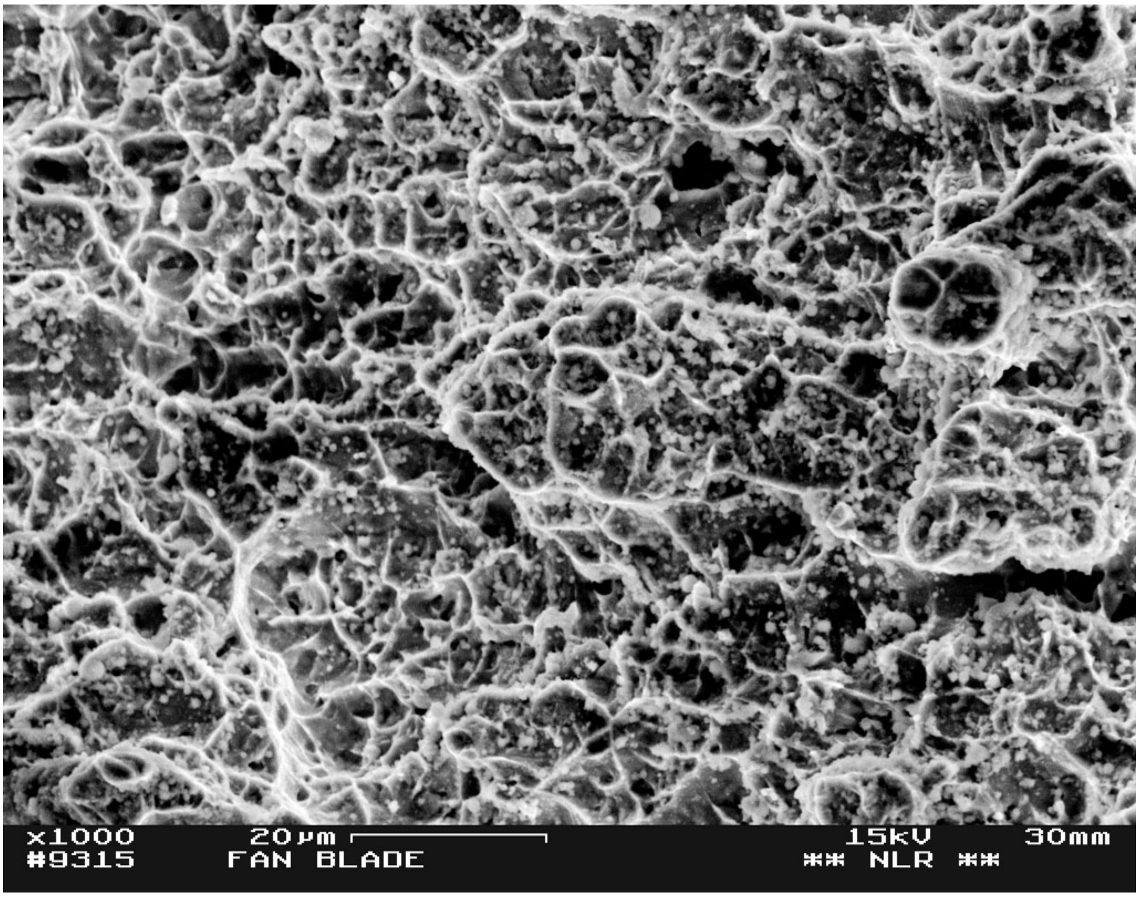


Fig. 12 Detail of figure 11, showing dimples characteristic for overload (SEM)

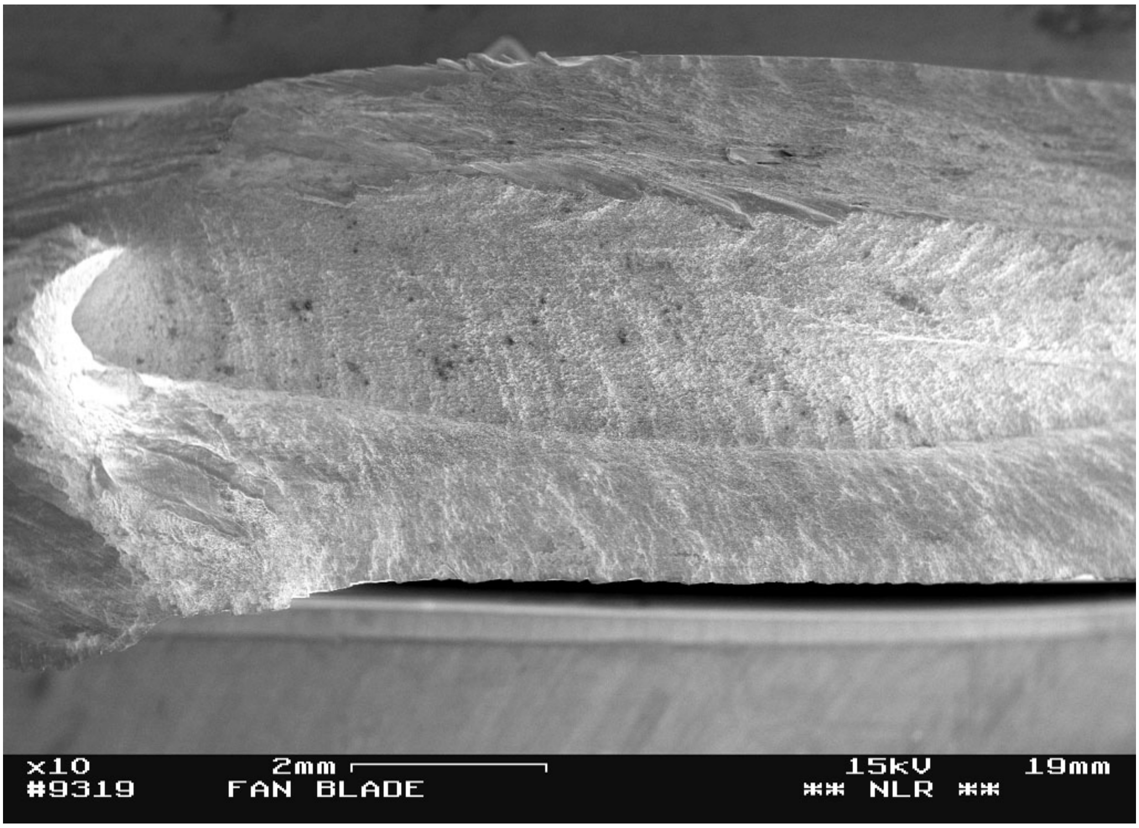


Fig. 13 Overview of fracture surface indicated in figure 3 (SEM)

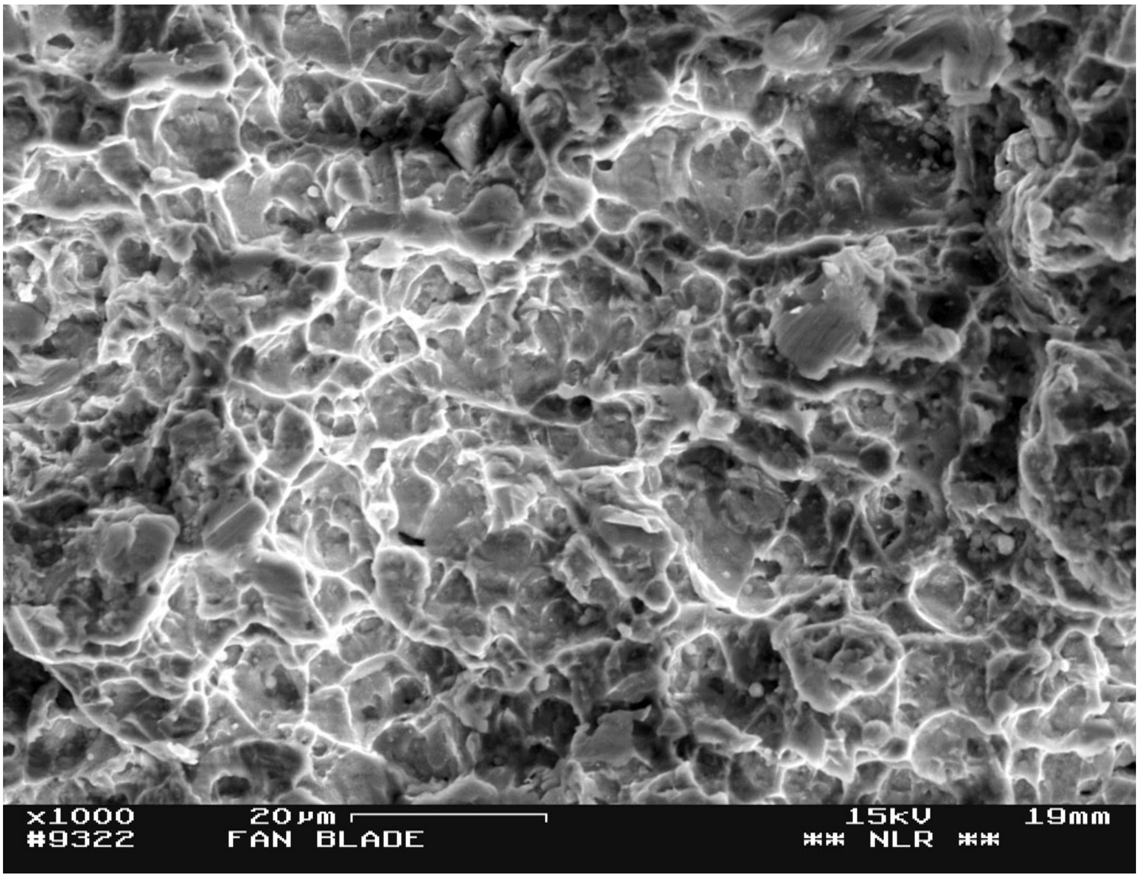


Fig. 14 Detail of figure 13, showing dimples characteristic for overload (SEM)

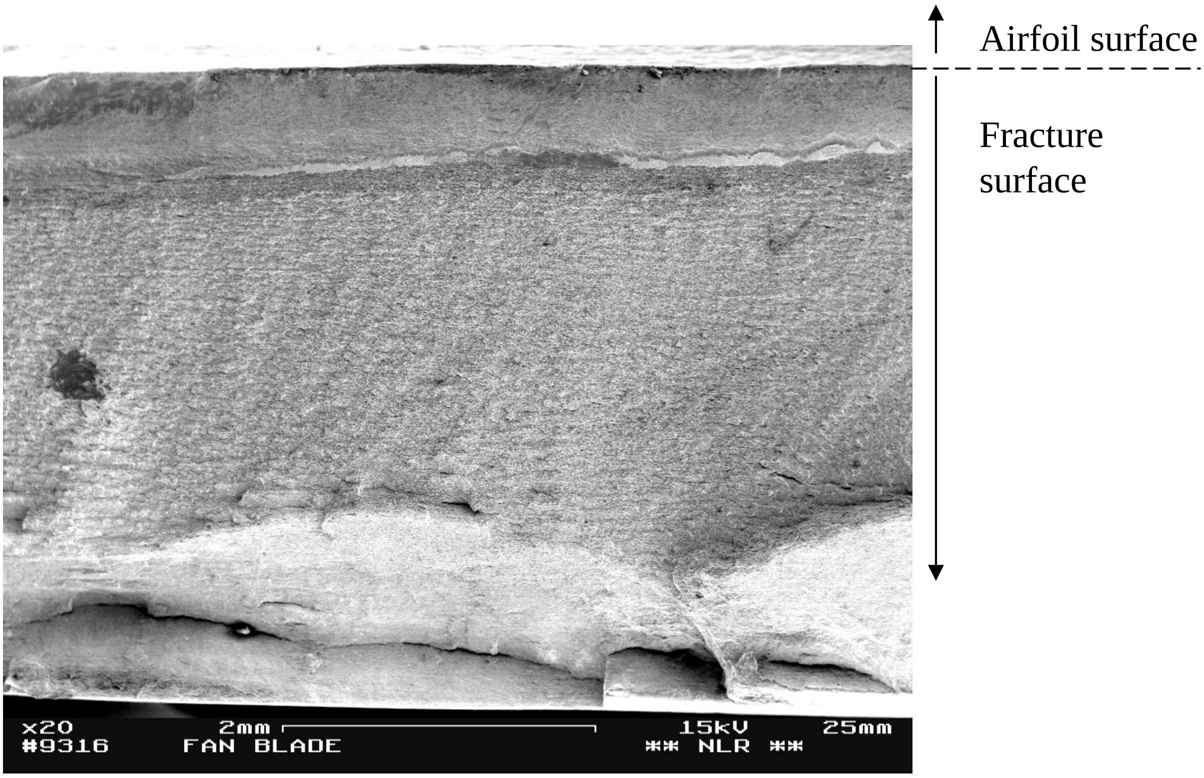


Fig. 15 Overview of straight fracture surface indicated in figure 6 (SEM)

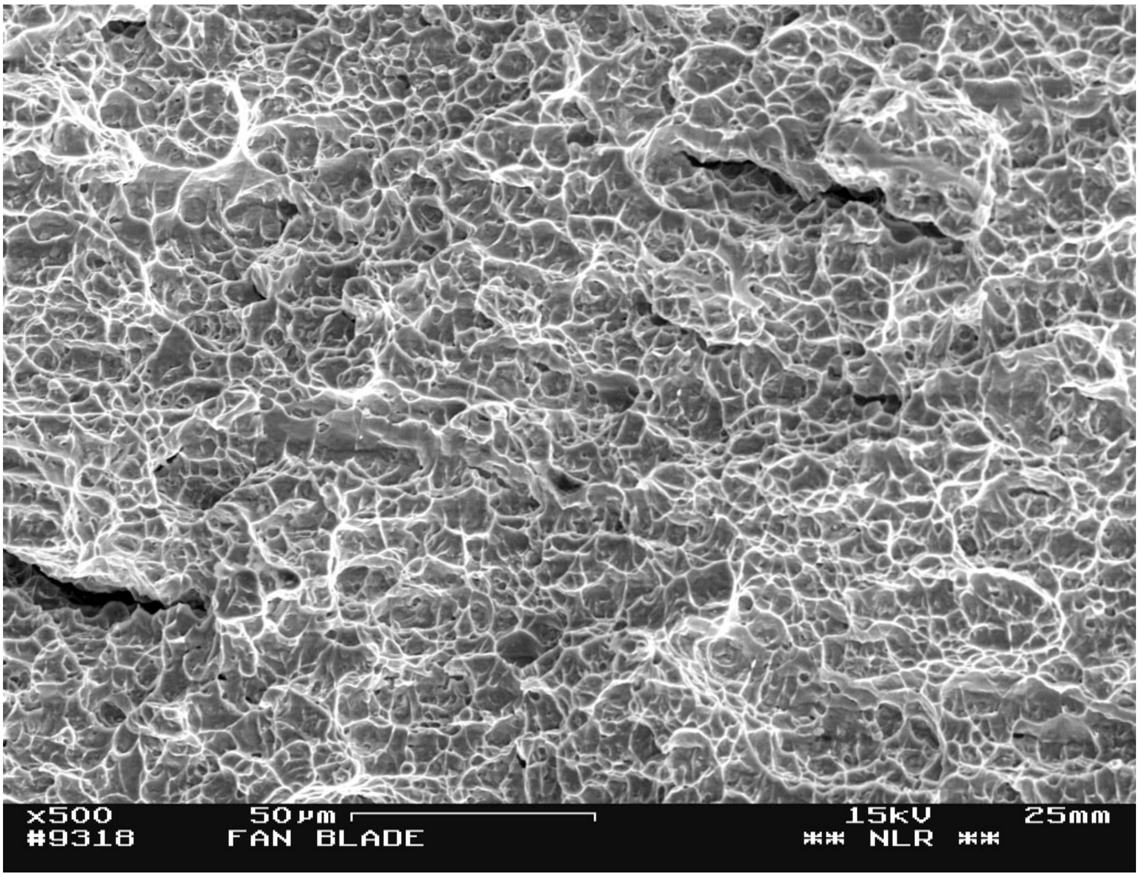


Fig. 16 Detail of figure 15 showing dimples characteristic for overload (SEM)

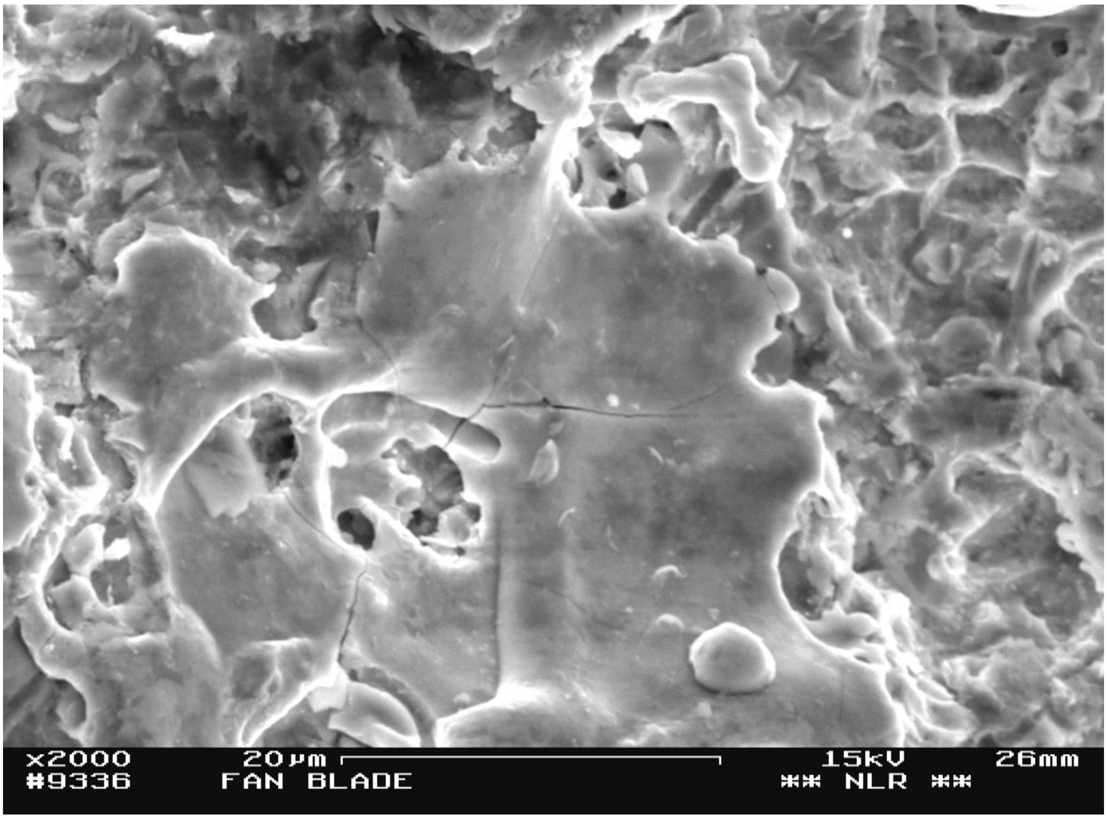


Fig. 17 Detail of the fracture surface between midspan shroud and inner airfoil (SEM)

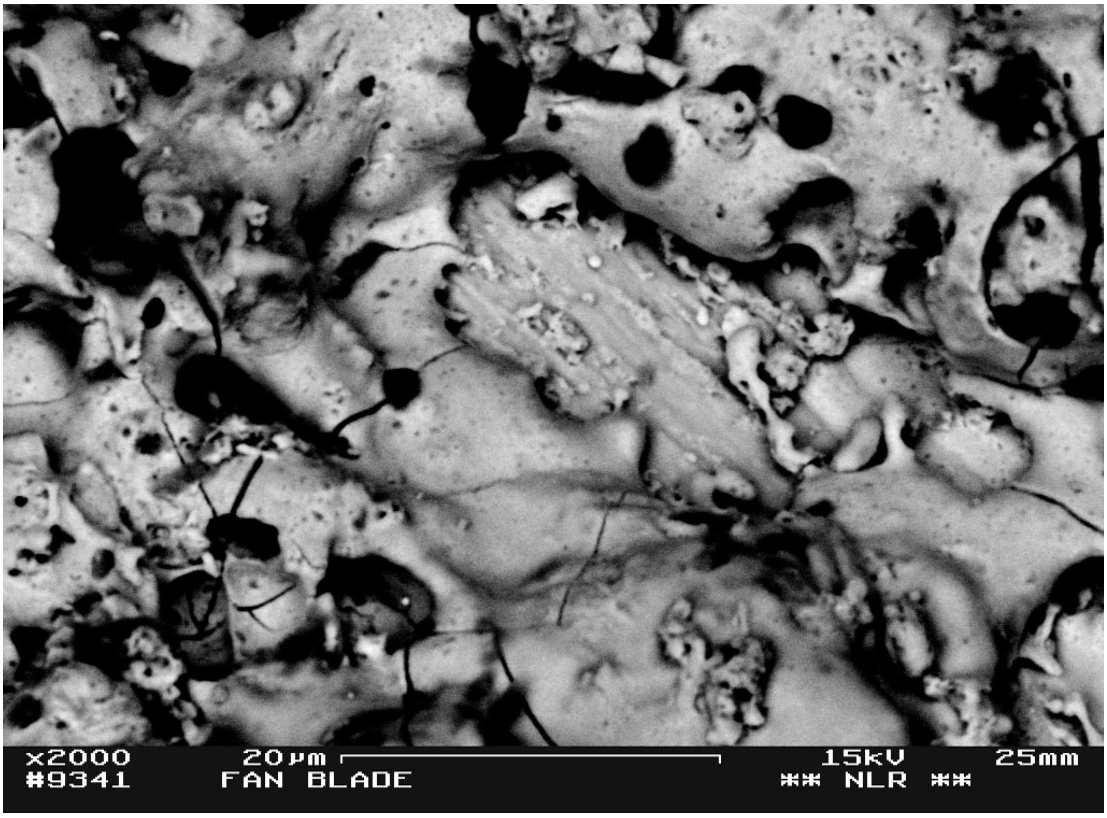


Fig. 18 Detail of the fracture surface between midspan shroud and outer airfoil (SEM)

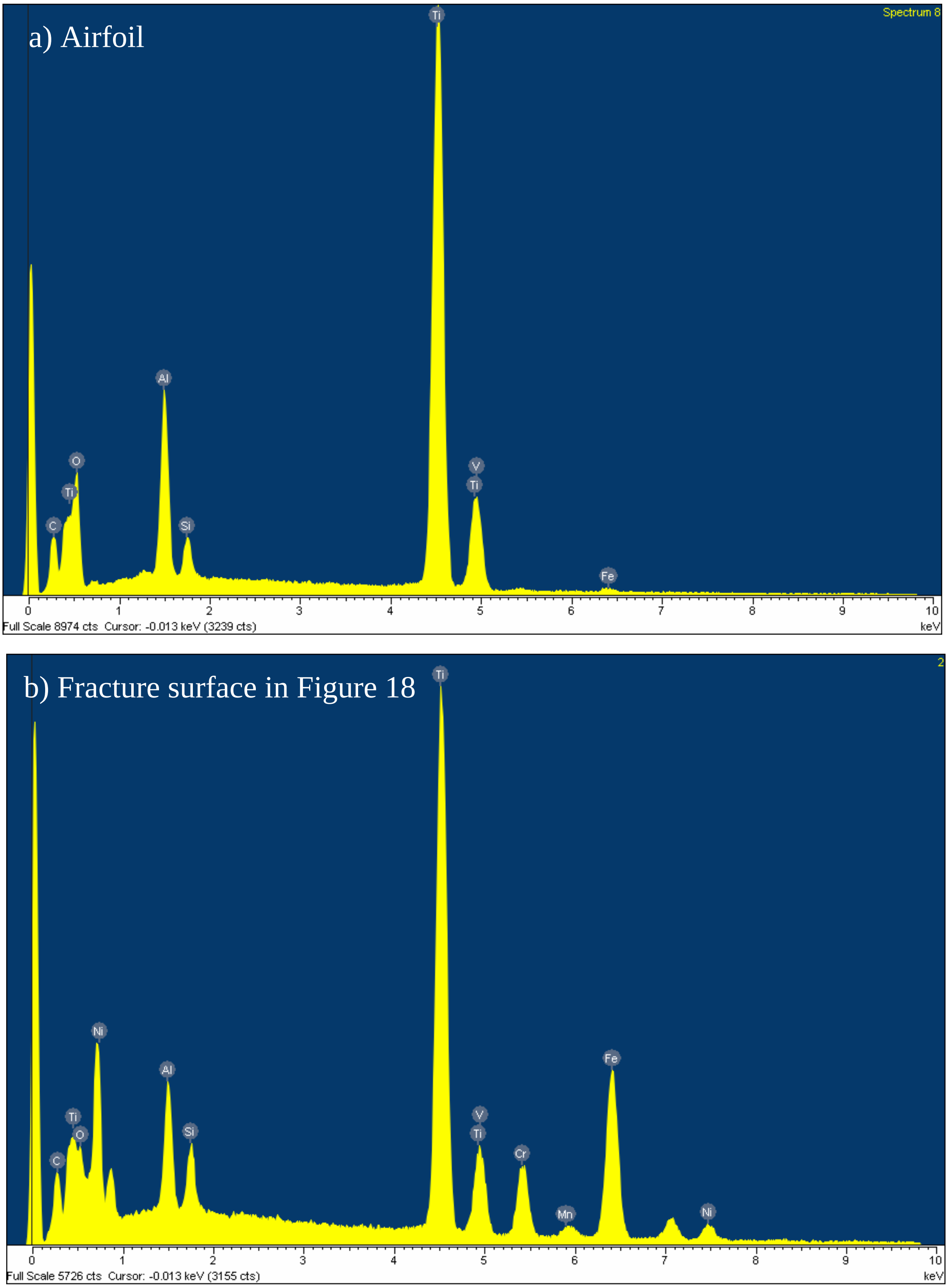


Fig. 19 EDX spectra at/near midspan shroud. Note the high Si and Fe peaks and the presence of Ni and Cr peaks in the lower figure as compared with the upper figure

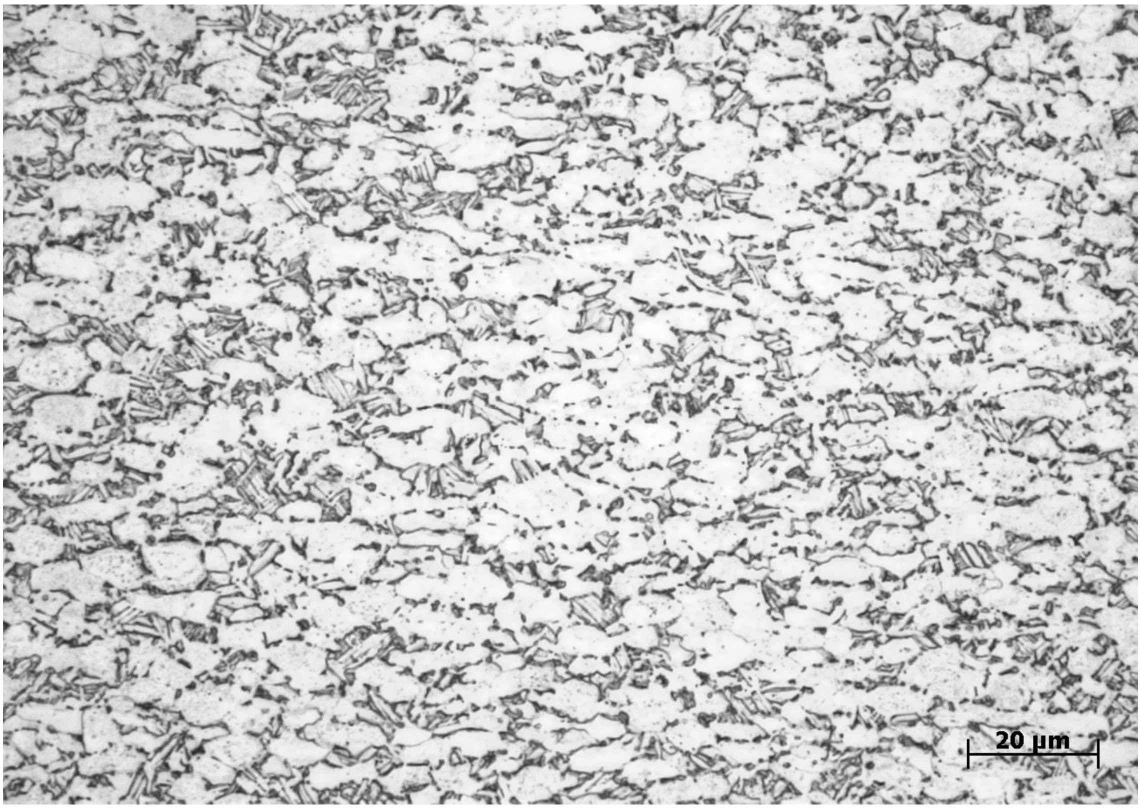


Fig. 20 Microstructure (OM)

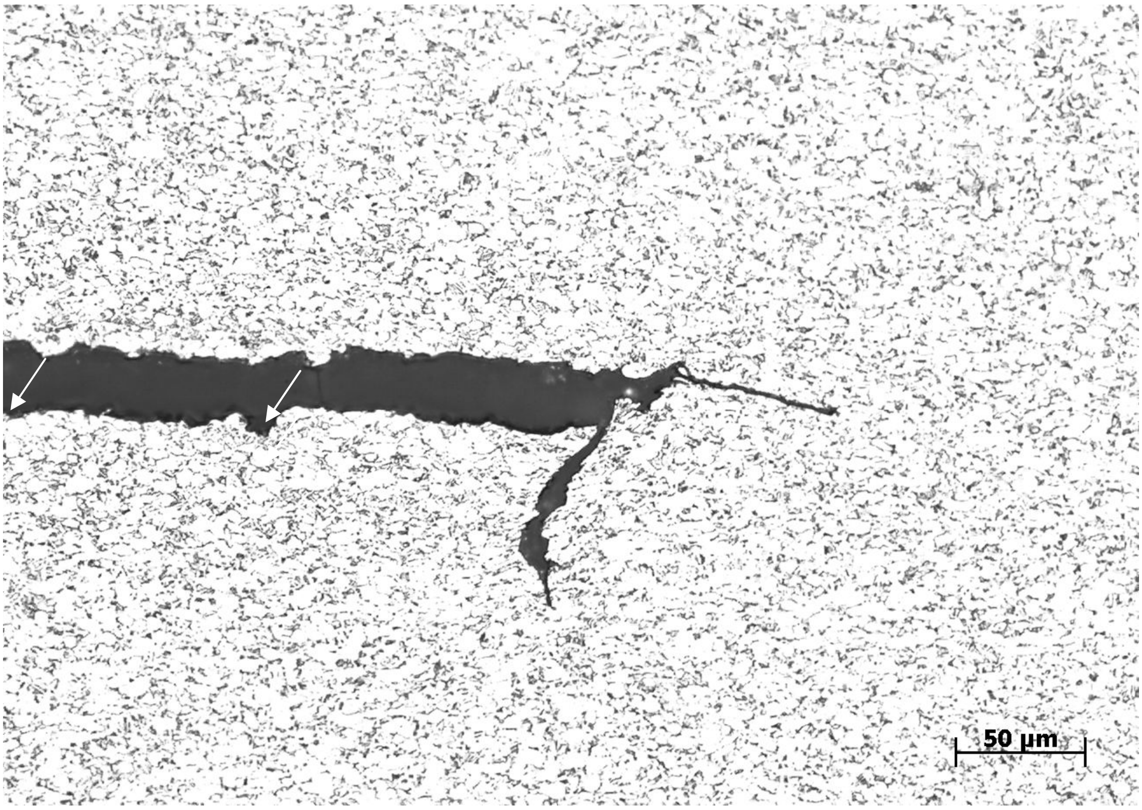


Fig. 21 Cross-section through the feature seen in figure 9 (OM). Note that the two fracture surfaces of the main crack seem to match (arrowed), that the fracture surfaces are rough and that the that the crack tips are sharp

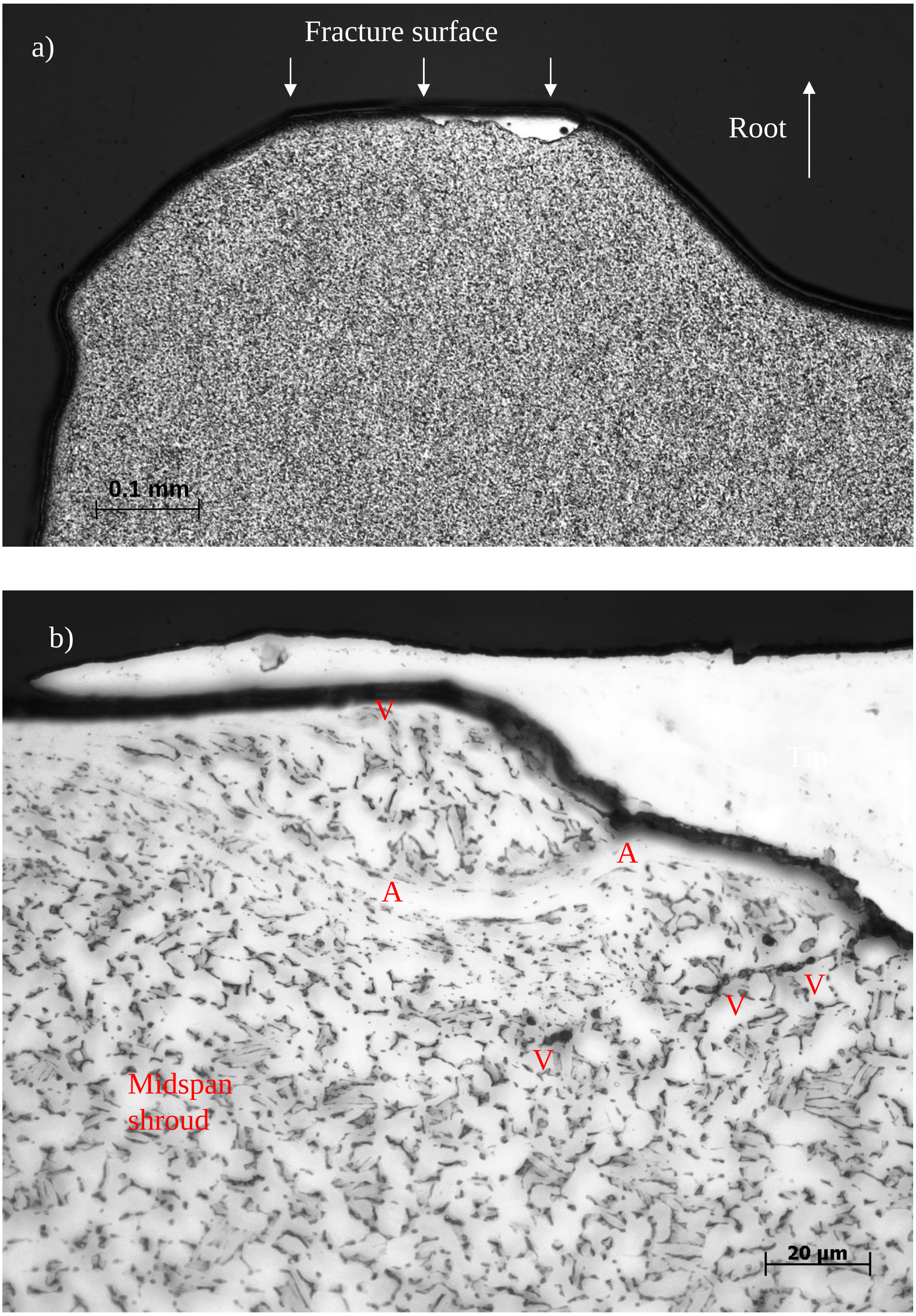
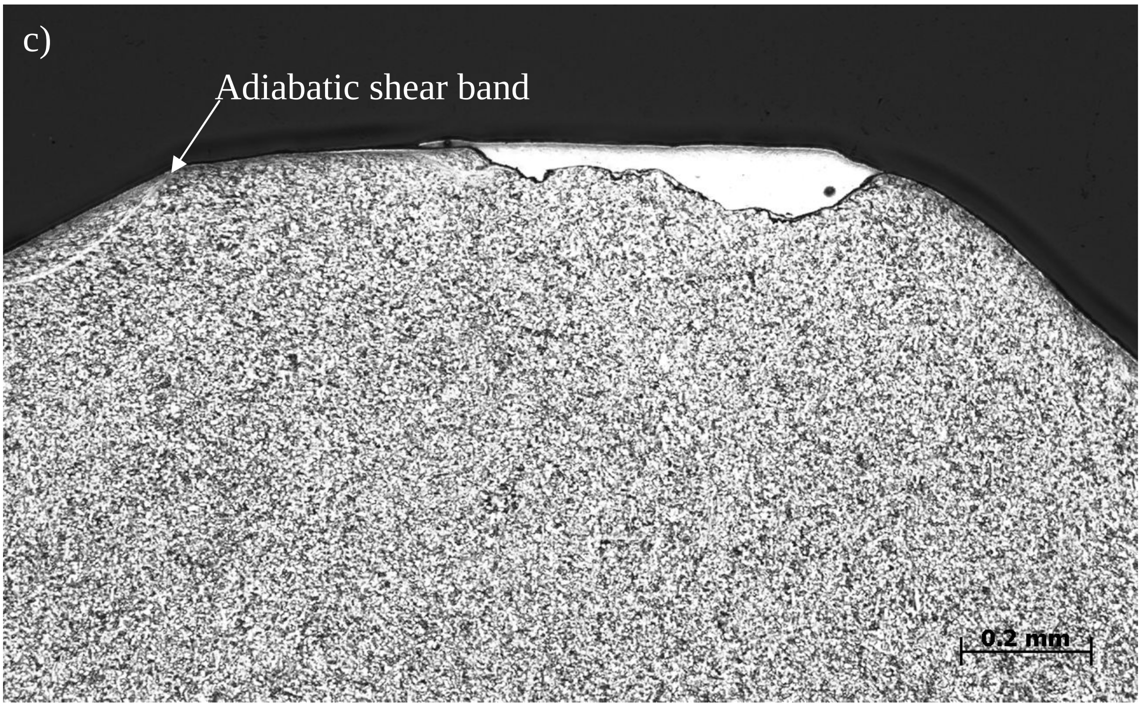


Fig. 22 Cross-section through the fracture surface in figure 18 (OM).
a) is an overview; b) –d) are details.
(continued on the next page)



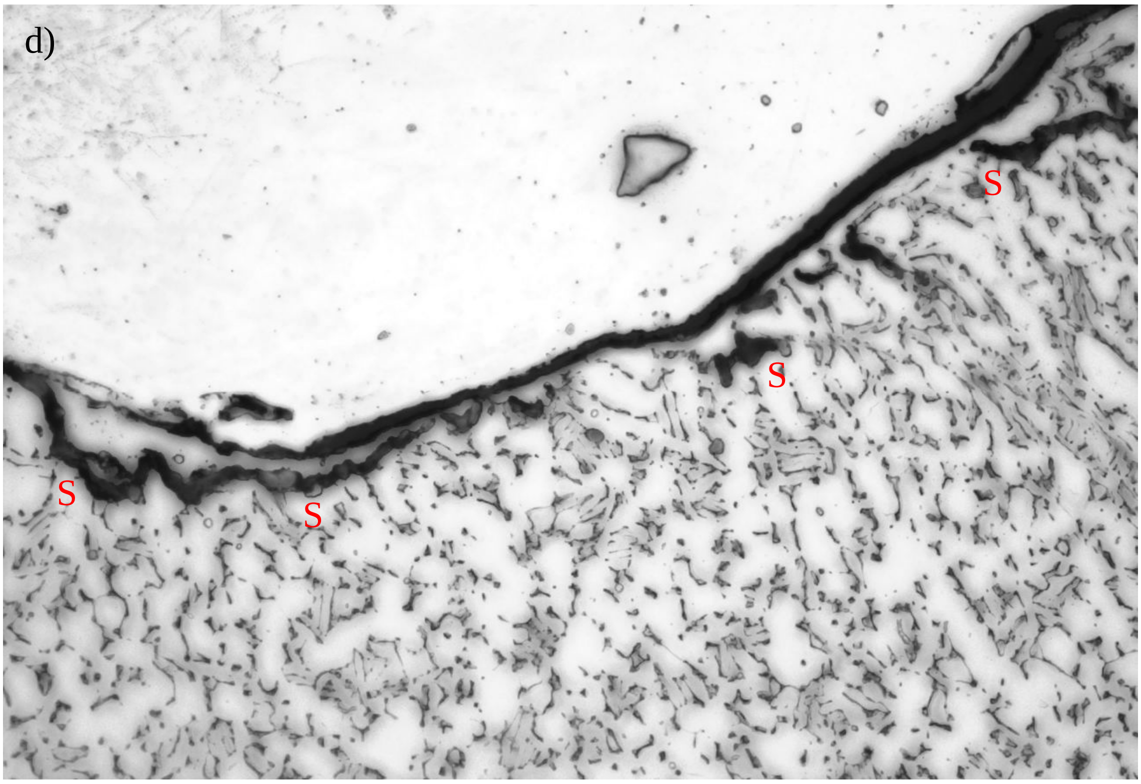


Fig. 22 (continued)
A: adiabatic shear band;
S: cracks thought to be caused by shock waves
V: voids;

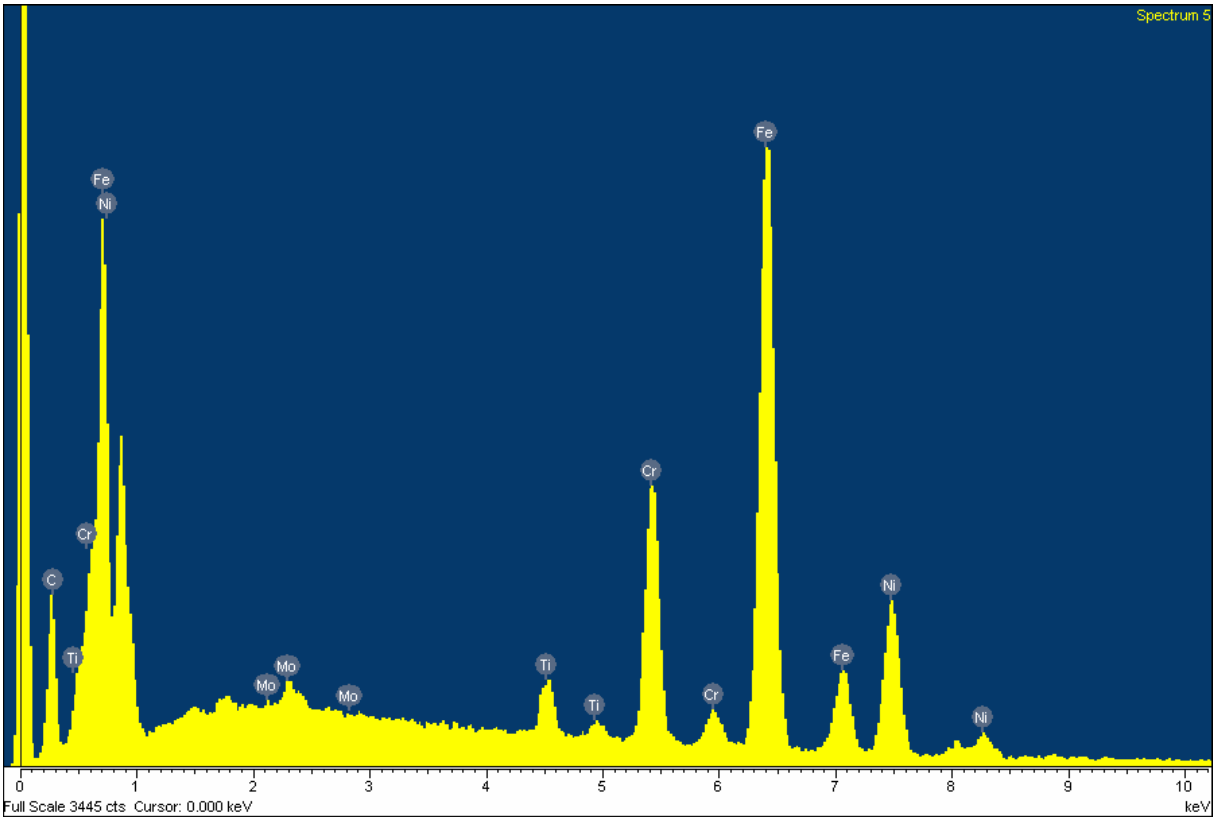
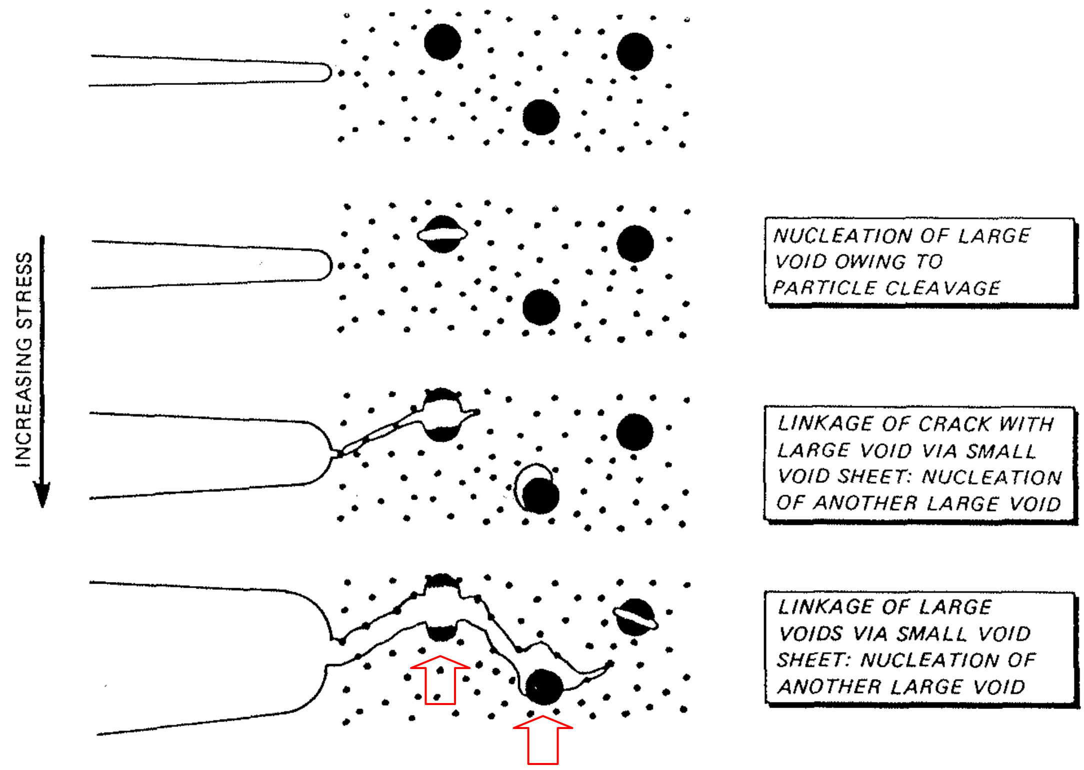


Fig. 23 *Example of EDX spectrum of the white layer in figure 22a*
The origin of carbon (C) is a carbon coating that was sputtered onto the specimen in order to prevent the charging of the cross-section by the electron beam

Appendix A Some expressions used in this report

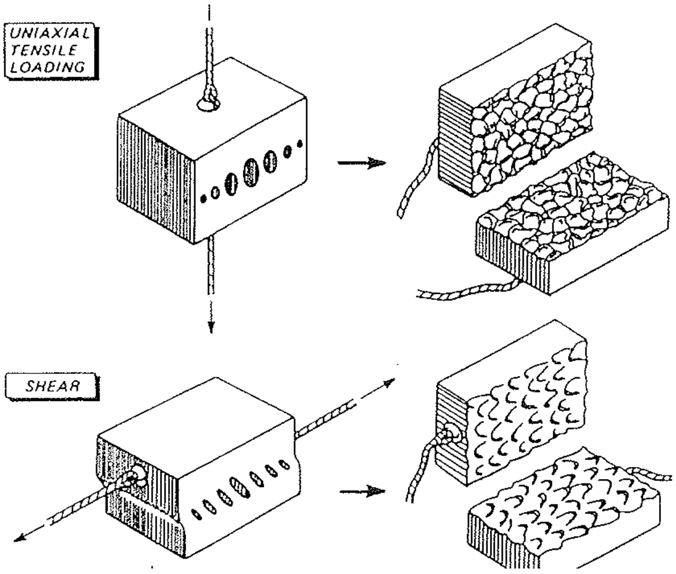
Dimples

The sketch below (taken from Ref. 7) shows the creation of dimples (arrowed) in front of a propagating crack:



The dimples do not necessarily contain the original particles (these particles can be contained in the opposite fracture surface or might fall out). Dimples are characteristic for overload failure. The geometry of the dimples depends on the way in which the force is applied, as illustrated in the sketch below:

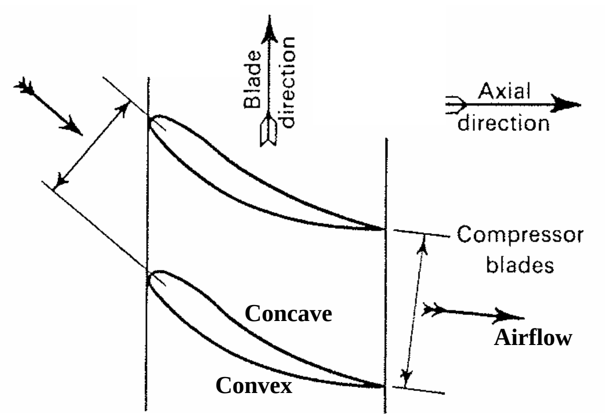
A uniaxial load gives rise to *equiaxed* (i.e. about circular) dimples. Because of this dimple geometry a crack direction cannot be deduced from the fracture surface. Shear gives rise to elongated (elliptical) dimples.



Forging lap

Upon forging a component of a certain desired shape is produced by deforming a piece of metal at a high temperature. Since forging is done in air, the surfaces of the original piece of metal will be covered with an oxide layer. A forging lap (also called: “cold shut”) is a part of this oxide layer that became encapsulated in the interior of the component during the deformation process. Since metal oxides are brittle, forging laps are weak spots. Such a defect can be recognized e.g. by detection of the oxygen in the oxides by means of EDX.

Geometry



The sketch (taken from a handbook) for compressor blades holds for fan blades as well.

In view of the blade rotation direction:

- Tip rub will cause an overhanging lip at the blade tip of the *convex side*.
- A Foreign Object (coming from the left hand side) will hit the *concave side* of a blade. The blade will bend backwards (downwards in the sketch) and this will introduce a tensile stress at the *concave side* and a compressive stress at the convex side. Blocking of the motion of the tip of a moving blade will have the same effect.

Hardness

The hardness of a metal is measured by indenting the metal surface with an indenter (a diamond, a steel ball or similar) with a known force. The load is applied for a standard time, usually 30 s, and the diameter of the indentation is measured with a low-power microscope after removal of the force. This diameter is translated into a numerical hardness value by means of a table or formula. For the same load a “hard metal” (i.e. a metal with a high hardness value) gives a small indentation diameter and a “soft” metal gives a large one.

There are several methods (e.g. Vickers, Brinell, Rockwell C, Rockwell B) to measure the hardness of a metal that differ in a.o. the indenter. In an investigation a certain method will be selected, depending on the availability of literature data for that method for the material under consideration.

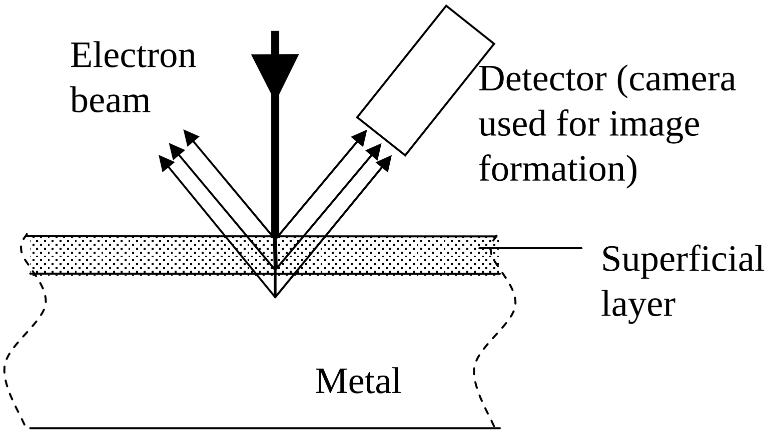
A certain metal can have different hardness values, depending on its heat treatment and deformation. The hardness of a certain metal is proportional to the ultimate tensile strength and fatigue strength. Hence the virtue of hardness measurements is that an idea on the mechanical strength of the metal under consideration can be obtained in a simple way and without using much material to make test specimens for tensile and fatigue tests.

The advantage of the so-called macro Vickers hardness is that its numerical value does not depend on the load. This does not hold for very small loads (i.e. for small indentations). For these so-called micro Vickers hardness measurements, the hardness values increases with decreasing load. Hence micro-hardness measurements can only be used for comparison with other measurements performed with the same load (as is the case here), but not for e.g. comparison with macro-hardness values in the literature.
Micro Vickers hardness measurements had to be applied instead of macro-hardness measurements since the limited thickness of the white layer in figure 22 could not accommodate large indentations.

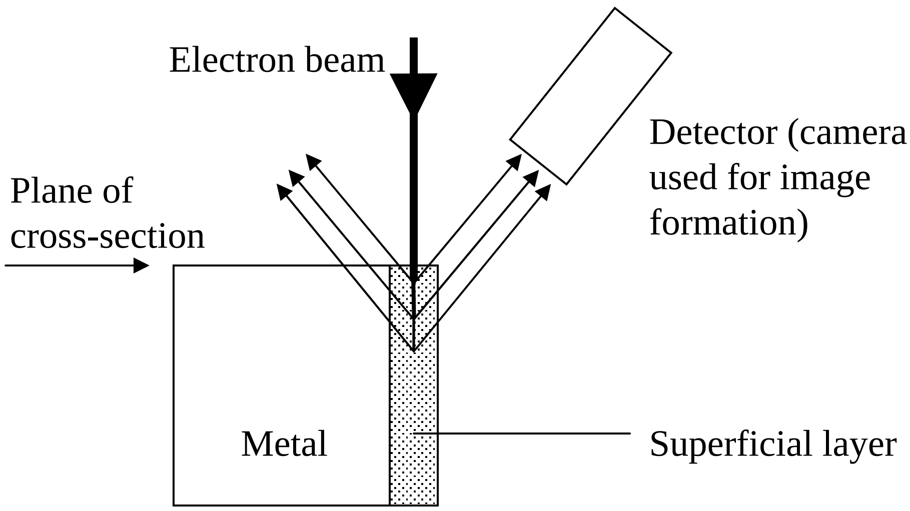
Mud cracking
This is cracking of a deposit on a fracture surface. The appearance of "mud cracking" indicates that a deposit (and not the fracture surface itself) is observed.

SEM (Scanning Electron Microscopy)
Simply speaking, a Scanning Electron Microscope can be regarded as an optical microscope in which the light beam is replaced by an electron beam. This results in a much higher magnification (over 20,000 X as compared with 1, 000 X maximum) and a much larger depth of focus.
Moreover, chemical compositions can be determined in a SEM by means of a special attachment, called an EDX detector.
(continued on the next page)

In this latter respect it should be realized that the electron beam penetrates into the material over a certain distance. Hence – if the component to be investigated is covered with a thin layer – the information originates from *both* this superficial layer and the underlying metal (see the sketch).



If information on the composition of the superficial layer only (or the underlying metal only) is required, a cross-section through the component should be made:



APPENDIX B. EXPERT INFORMATION FROM A GAS TURBINE ACCIDENT INVESTIGATION COURSE INSTRUCTOR

The Dutch Safety Board took the opportunity to share photographic information of this incident with a gas turbine accident investigator course instructor. It is mentioned, however, that he did not fully participate in considering all evidence and hands on examination.

As an expert the instructor was consulted for the Fly Air engine failure (General Electric (GE)). Besides this failure another engine failure (confirmed bird ingestion of a Pratt & Whitney (PW) engine) was discussed as also pictures of this event were exchanged. This explains why the instructor addresses more than only information and questions from the Fly Air engine.

In his comments he reflected the next analysis:

"*Yes, there is a big difference between the two events in Docs GE 127135 and the PW1271321. The PW event appears to be a single bird weighing 2.5-3 lbs (typical herring gull size), while the GE event appears to be compatible with a pigeon or owl weighing less than a pound. Of course I understand your point about the lack of positive evidence of bird remains for the GE event (small object) and of course you must acknowledge this in your factual report. However it is very positive that both events involved the ingestion of a single soft body object of the sizes that I specified. You may note that in both events the object was sliced in such a way as to correspond with an oglive spheroid shape (like a bird, not ice).*

Yes I agree that blood feathers and smell are key ingredients, but in the case of large high bypass engines with a single small bird out the fan duct it is slightly more problematic to find such evidence after several hours of drying out in the air.

I also accept that cusps may result from lower RPM ingestion events but only in the rarest of events where the engine is at or below idle and then the cusps will be randomly located around the rotor face and not in a cascade fashion associated with a sliced object.

The essence of the investigation should associate itself with the size of the ingested object versus the damage to the fan.
In either event some discussion and background needs to be made of the bird species and flocking behaviour under the airport bird control environment. Large flocking birds allowed to loaf on or near runways are a major concern, while a single non-flocking bird is of much lesser concern even in the presence of a single engine power loss such as the GE event.

Now for some discussion about how blades fracture in the presence of soft body FOD. In order to keep this simple I will confine my comments only to part span shrouded blades of the size and aspect ratio associated with non-inlet-guide-vane engines like the CF6 and JT9D series involved in the two events. These explanations should not be extended to engines whose blade aspect ratio is associated with inlet-guide vanes or large unshrouded wide-chord fan blades on the B777 etc.

In the subject blades the soft-body caused cusp creates a membrane stress field (like an overripe tomato) at the very leading edge and progresses aft and in span length as the bird's body increases in size. Ultimately the membrane stress may cause a transverse crack to form in the blades' leading edge. Even if the membrane stress is not exceeded in the leading edge, if the cusp intercepts a significant change in section associated with the part-span shroud location a step increase in stress occurs in plain strain forcing an eyelash type crack to form around the change in section at the partspan shroud. Ultimately the bird action against the blade changes to a smooth hydraulic loading as it is pumped aft and then results in a significant twisting action (the partspan shrouds jump over each other) which can cause any initially formed cracks to jump into a step change exhibiting torsional fracture in a transverse direction. This is much more common for large birds greater than 2 lbs.

However if a pre-existing notch is present in the leading edge of a blade (possibly from a very small stone ingestion) then the impression of a maximum membrane soft-body caused cusp directly on this notch will result in a shear crack emanating from this notch and together with the torsional loading described earlier may result in a transverse fracture of the blade even with a small bird. If the very initiation site of the fracture in the GE blade event is examine the metallurgist may find the pre-existence of a small FOD crater of 20 mils or so and a small shear tear at the bottom of the crater of some 5 mils followed by tensile shear induced by the soft-body membrane stress followed by a change over to torsional shear transversely across the blade."