Enhancing Safety Through Engineering Analysis

– The ATSB Technical Analysis Unit

Introduction

Aviation is a technical business. From the days when the first Wright Flyers took to the skies, engineers, technicians and designers have struggled to deal with the vagaries of taking to the air in a mechanical machine and returning safely to the earth. Even in the present age where technology has increased beyond the wildest imagination of those early pioneers, we have yet to produce a flying machine that is faultless in its performance – one that is incapable of failing to operate in the manner intended.

Trial and error. Learning from mistakes. We all live by these techniques. Humans are not born with knowledge – we learn from experience. We design and analyse, redesign and reanalyse. When we think we have it right, we build and we fly. And unfortunately, sometimes we crash.

Humans are fallible in everything they do. We cannot build the perfect aircraft because we are incapable of doing so. This is why learning from experience is the most powerful tool we have in our pursuit of successful safer engineering.

To learn from failure, we must first gather the facts: human factors; operational factors; environmental factors; technical factors.
Some remarkable tools have been devised to help us investigate the technical. Wonderful machines that record volumes of data and can survive the most unimaginable accident conditions. Powerful microscopes that can image the micro-features of fractures. From the information provided by these tools, we can begin to develop an accurate picture of 'what went wrong', and thus make the changes to prevent a recurrence. In the process, we benefit from an improved understanding of the issues and an increased knowledge base from which to work.

The ATSB Technical Analysis Unit (TAU)

The Technical Analysis unit in Canberra is charged with the responsibility of applying engineering science to the investigation of transport safety occurrences. Within the unit, this occurs in two main areas:

- Recorded Information Analysis

  Recorded information is typically found in two forms – data and audio. Recorded audio originates cockpit voice recorders and air traffic services tapes; recorded data from flight data recorders, quick-access recorders and ATS radar tapes. Two primary steps are involved in gleaning information from these sources – recovery and analysis. Each often requires extensive use of dedicated software packages to download and verify the data and then analyse and present it in a form that is readily interpretable.

- Physical Evidence Analysis

  Dealing with the examination of failed equipment and damaged articles, this avenue of investigation focuses on component failure and material performance issues. Analytical study of a damaged or failed item can yield a great deal of historical information about the conditions under which it was operating prior to failing. Fracture surfaces are particularly valuable and can present a very characteristic indication of the magnitude, direction and nature of the applied loads.

How the Technical Analysis Unit Interfaces

The TAU interfaces with the other ATSB sections and the external industry on a number of defined levels.

- Investigation Support Services

  This focuses on the examination of physical evidence – often as part of a team investigating a safety occurrence. Such work may include the characterisation of a mechanical failure, the analysis of aircraft performance from radar track or the identification of aural warnings sounding within the cockpit.

- Direct Investigation of Safety Occurrences with a technical basis

  Engine failures, landing gear malfunctions and structural cracking are typical of the types of occurrence that may be investigated directly by the Technical Analysis team.

- Industry Safety Liaison

  The TAU provides an informal avenue for discussion of technical issues relating to equipment and component performance issues. The team is always keen to discuss concerns and provides a point of contact for the notification of safety occurrences of a technical nature.

- Safety Studies

  Often the scope of an individual investigation does not allow for a full study of all the facets of an identified safety issue. Perhaps the technical issues uncovered were of a secondary or minor significance in the actual occurrence, however they may still warrant pursuit in their own right. These issues are typically the basis of a safety study, which often brings together the information gained from multiple separately investigated occurrences. Outputs are generally broad recommendations or discussions aimed at increasing awareness of the issues at hand.

The Value of Engineering Analysis

The case studies following are presented to illustrate the types of information that can be gained from the technical analysis of a safety occurrence. Both deal with in-flight engine shutdowns resulting from the development of relatively small technical problems. While the occurrences were unrelated, they both served to demonstrate the value of in-depth technical studies in determining the root causes of the events.

Case Study #1: The Impact of Secondary Accessories on Primary Engine Reliability – Electrical Discharge Damage

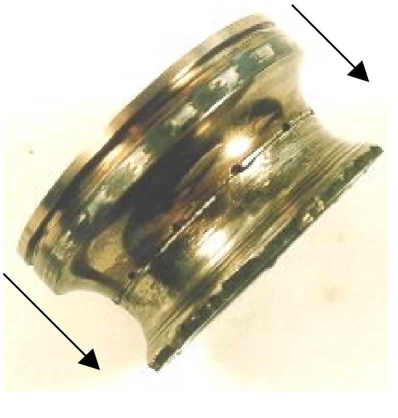
A twin-engine RPT aircraft fitted with modern and common turbo-prop power plants experienced an uncommanded auto feathering of one engine in response to an engine compressor failure. The subsequent strip examination showed the primary shaft bearing to have overheated and seized against the races, producing extensive wear and damage (figures 1 & 2).

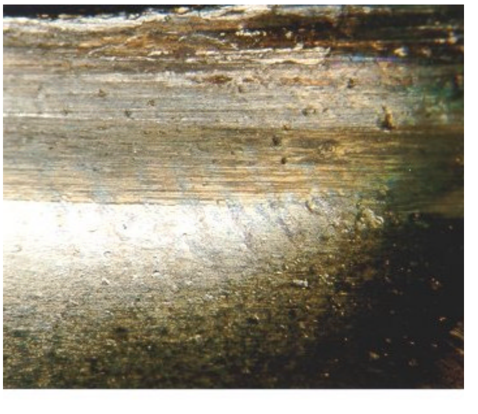
Figures 1 & 2. Destroyed main shaft bearing as recovered

When bearings suffer breakdown and failure, there is generally a very significant increase in frictional heating that often leads to thermal runaway and extensive surface melting. The case in question was no exception and considering the high turbine shaft speeds, the progression of the final stages of this failure would have been rapid.

The primary question to be answered in this investigation was the reason for the failure of the shaft bearing. Bearings fail for numerous reasons - most of these result in an increase in friction to a point where the lubricant, bearing materials or both completely fail. Seizure will be the inevitable result in most cases if the breakdown is not detected soon enough.

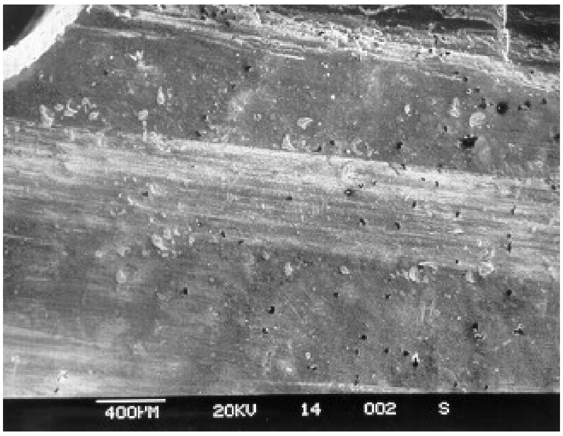
In this case, bearing seizure had occurred, with extensive accompanying heat and wear damage to the balls, races and cage. Due to the effects of compressor thrust loads, the wear on the inner races was biased toward one side, leaving one half of the raceway able to be studied in more detail (figures 3 & 4).

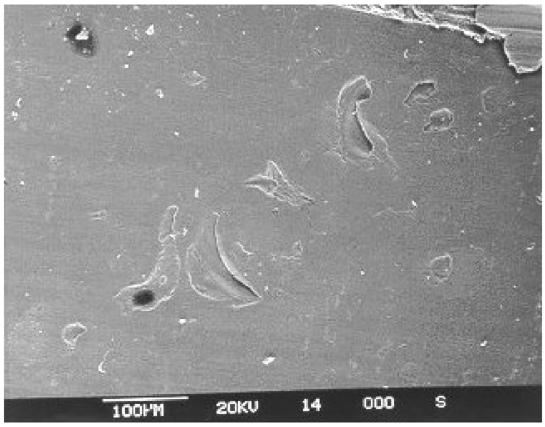


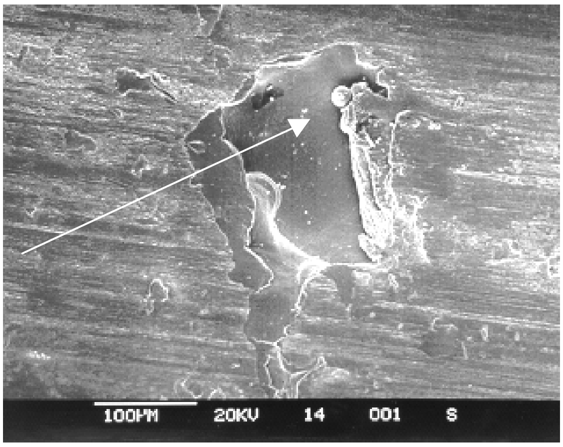


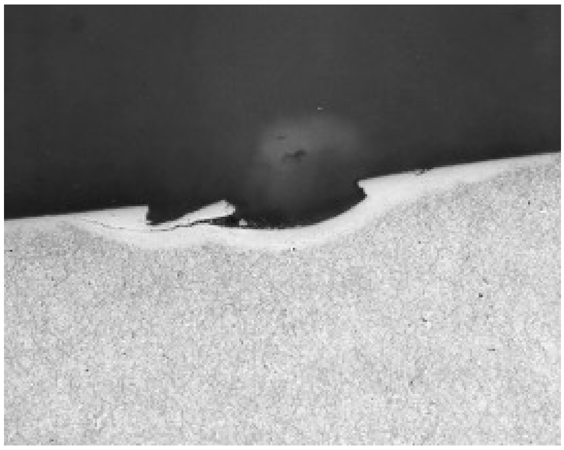
Figures 3 & 4. Inner race damage and pitted appearance of the race surface under magnification

Scanning electron microscopy provided the key. Small pits found toward the inner edge of the race showed characteristic evidence of electrical arcing damage, including small globules of remelted race material within the pit confines (figures 5, 6 & 7). Metallographic sectioning and examination of the race microstructure surrounding these pits showed prominent light-etching transformed zones, typical of localised heating and characteristic of arc damage (figure 8).









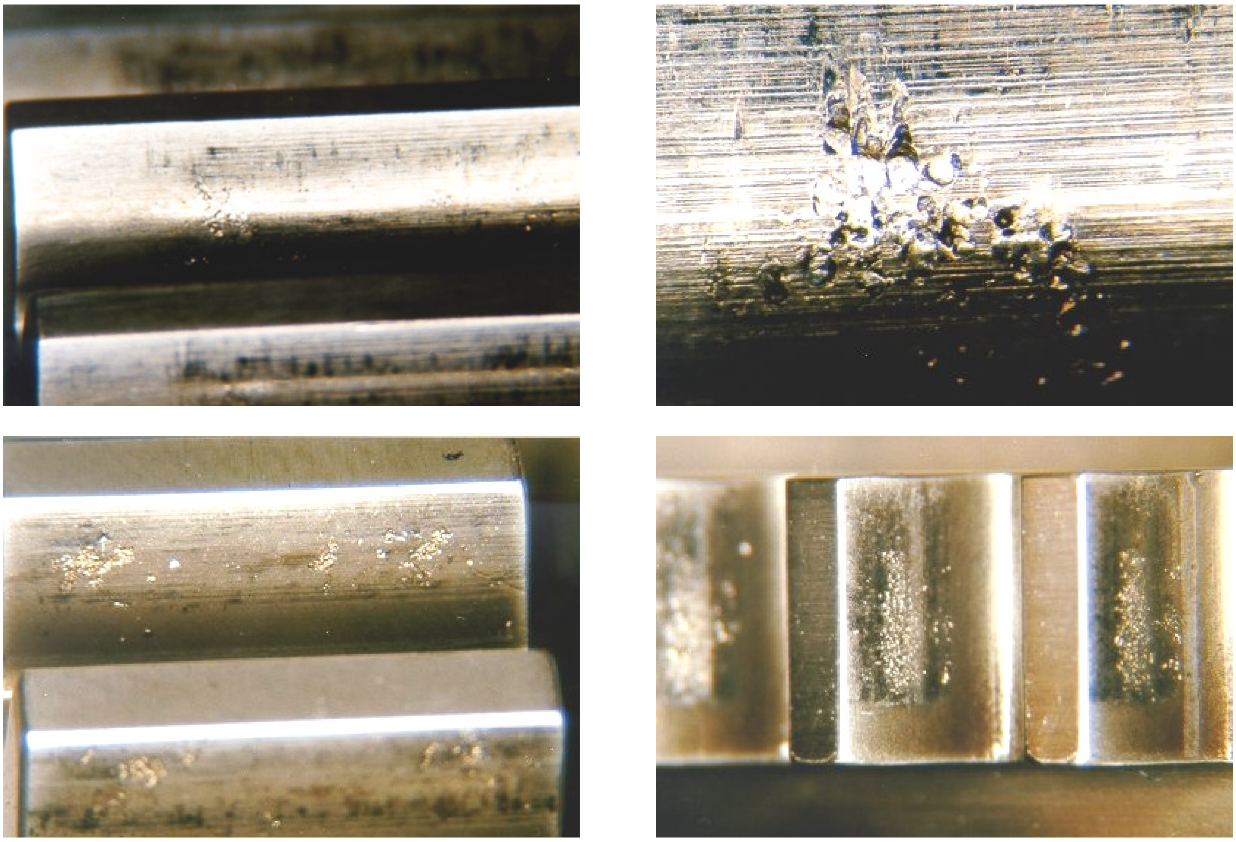
Figures 5 & 6 (Top). Inner race surfaces under the SEM, showing the typical pitting form.
Figure 7 (Btm L). Closer view of a pit showing the globule of re-melted material, typical of arc damage.
Figure 8 (Btm R). Metallographic section through a surface pit, showing the surrounding light transformed region.

So there is the answer – the bearing failed from electrical arcing damage that produced:

- Pitting of the contact surfaces
- Interruption of the normal rolling contact between the bearing elements
- Increase in frictional heating
- Thermal runaway and seizure of the unit.

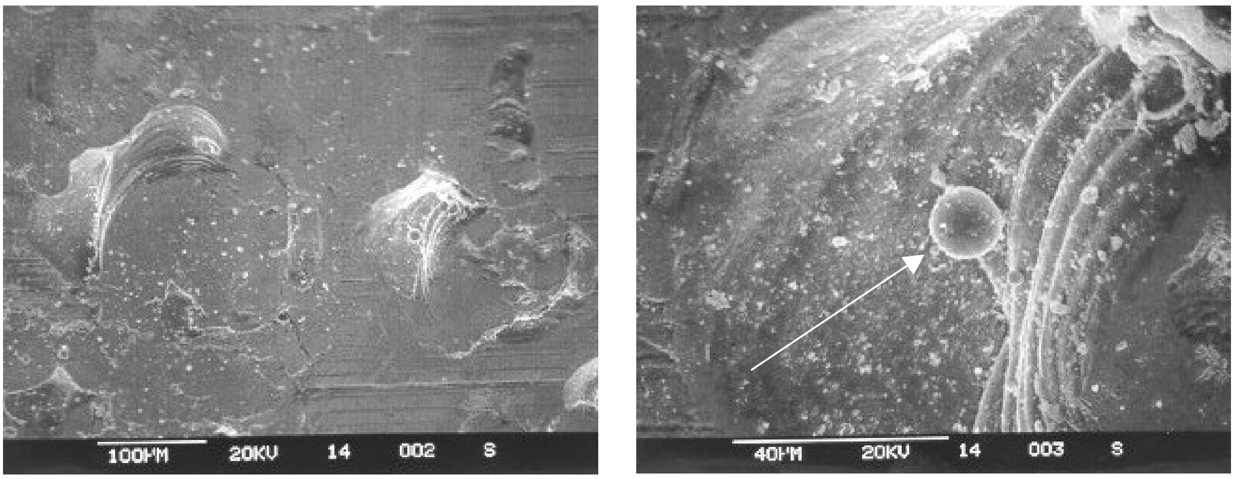
How did this damage occur? Was it a result of a single surge, such as may occur from a lightning strike? Was it a progressive development over a period of time? The answers here came from an examination of the components surrounding the shaft bearing.

The main shaft of the turbine was coupled to the accessory gearbox via a short splined shaft and a series of reduction gears. The accessory gearbox carries the starter / generator for the engine and aircraft electrical services. Each of the drive train components leading from the main shaft to the starter-generator showed small areas of surface pitting damage in the areas of contact with the adjacent components (figures 9 – 12).



Figures 9 - 12. Pitting from electrical discharge found on the contact surfaces of the accessory gearbox gear teeth.

The gear faces presented damage which appeared to be spalling or rolling-contact fatigue damage. Closer scrutiny however, again under the electron microscope showed the damage to be very similar to the bearing race pitting – having all the hallmarks of electrical discharge damage (figures 13 & 14).



Figures 13 &14. SEM views of gear teeth pitting, again showing clear evidence of re-melting.

Additionally, patterns were found within the distribution of the damage around the starter gear that suggested the current was alternating in potential in phase with the gear rotation. Logically, the markings also indicated the direction of current flow to be away from the starter generator (figure 15).

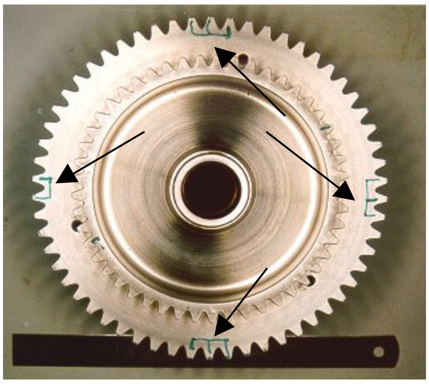


Figure 15. Starter gear profile view showing the dominant locations of electrical discharge pitting.

In this way, it was possible to confirm the starter-generator unit as being the source of electrical leakage current, which sought the path of least resistance down through the accessory gearbox and into the number one bearing. Tests have subsequently confirmed that the starter-generators in question can produce an alternating current on the armature shaft when certain conditions exist.

Issues

This occurrence was a good example of the potential for the interaction between systems in a way that can produce a damaging outcome. It is crucial in any engineering analysis to identify the root cause of a failure or breakdown. If this is not achieved the potential for recurrence remains.

Using this occurrence as an example, we have an in-flight engine failure that results from the failure of a main shaft bearing. No question.
On first examination, pitting damage to the bearing and surrounding gears could be attributed to contact fatigue spalling – leading to questions about loads, lubrication and so-forth. Accurate engineering analysis was however needed to demonstrate that electrical discharge damage was in fact the culprit. Indeed, the patterns of damage found indicated both the source and nature of the current flow. In this way, potential problems with the starter-generator unit could be identified and later tested to confirm the suspicions raised.

The root cause of this failure was thus a fault within the starter-generator unit, allowing leakage current into the accessory gear train and producing damage to the main bearing, rendering it incapable of continued low-friction operation. It would further be expected that the analysis process would be continued to identify the nature of the fault within the starter-generator and why that fault originated.

Interestingly, if this process is continued fully, it is inevitably found that in almost all cases, human factors issues arise as the fundamental causes of all engineering deficiencies.

Case Study #2: Service Life Issues with Repaired HP Turbine Blades

A large twin-engine passenger airliner suffered a sudden and dramatic failure within one engine soon after take-off. The engine was quickly shut down and the aircraft safety returned to the aerodrome.

The subsequent engine strip examination showed very extensive damage to the low-pressure turbine blades of all four stages. Most blades had fractured at the root or mid-section and created a large amount of debris which carried through the turbine (figure 16). Exposure of the high-pressure turbine disk showed only one blade to have any damage – this being the loss of a 15 x 20mm section from the tip trailing edge (figure 17). All other HPT blades were intact, although many contained radial notch-like cracking from the tip edges on both concave and convex sides (figures 18 & 19).

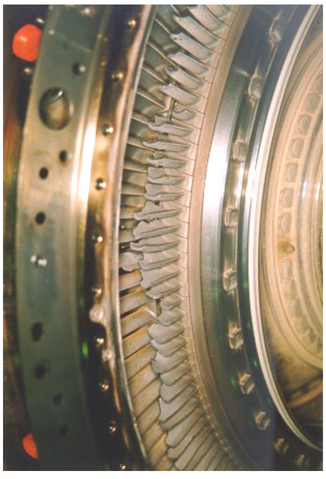
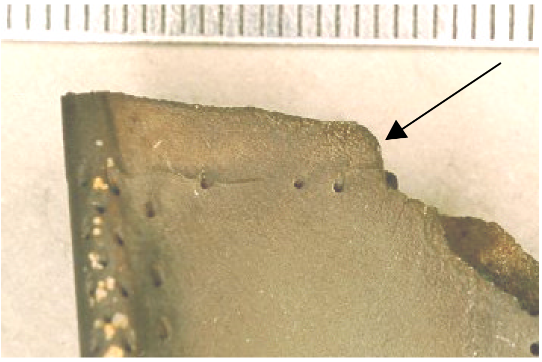


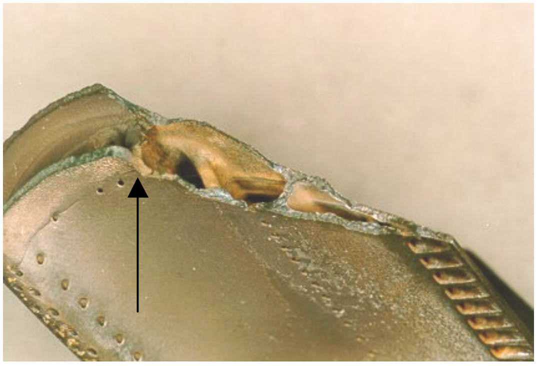
Figure 16 (Left). Damage presented by the first stage low-pressure turbine blades.
Figure 17 (Right). Damage shown by only one blade of the high-pressure turbine.

Figures 18 & 19. Cracking and notching of the tip edges found on many of the HPT blades.

Given that no significant damage or loss of components was found forward of the HPT stage, it appeared likely that the loss of the segment from the HPT blade had caused the 'avalanche' collapse of the downstream blades. Supporting this, all examined LPT blades were confirmed to have failed in overload.

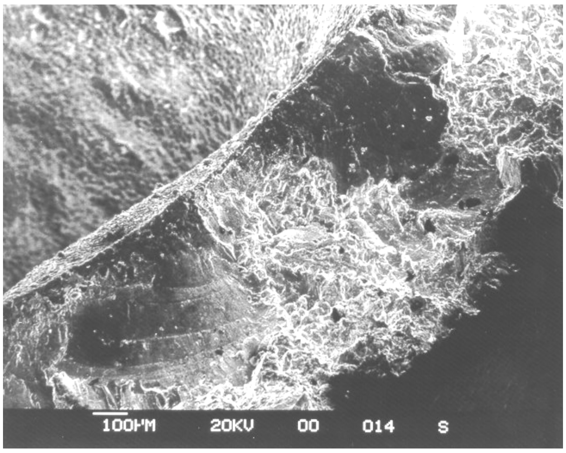
Why did the HPT blade liberate a segment? This was the question driving the examination and led to the close visual and metallurgical inspection of the failed component. The radial tip notching effect observed on many other blades was quite prominent on the failed item and was located at the tip end of the liberated segment, suggesting the influence of this phenomenon (figures 20 & 21).

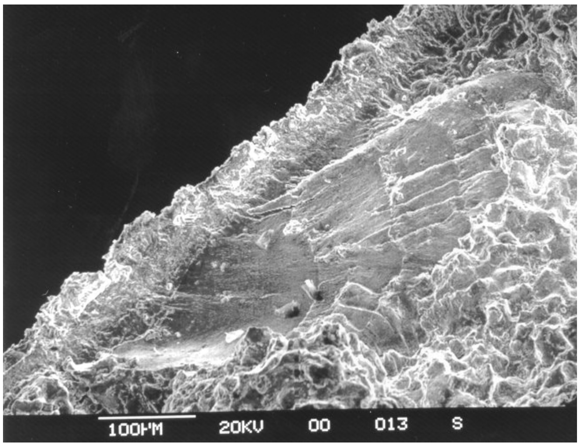




Figures 20 & 21. Failed HPT blade showing the orientation and size of the liberated section. Note also the effects of the tip notching (arrowed).

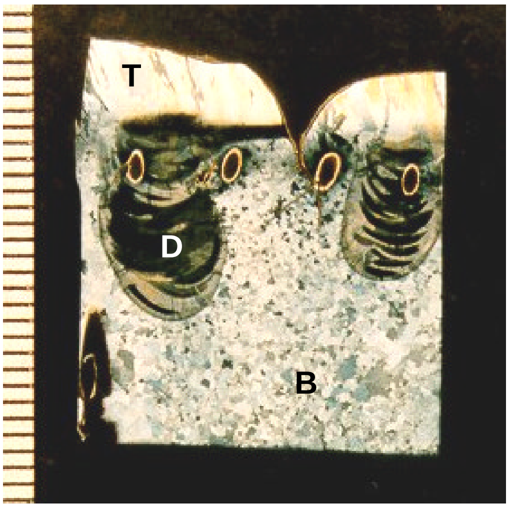
Electron microscopy revealed good evidence of the fatigue propagation of cracking beyond the notched area (figures 22 & 23). The orientation of the fatigue beach marks indicated blade thrust loads were a dominant driving force. The absence of excessive high temperature oxidation of the blade edges (from the loss of cooling air flow) indicates that the engine had been shut down very shortly after the blade segment was lost – additional evidence that the HPT blade failure caused the downstream damage.





Figures 22 & 23. Clear evidence of fatigue cracking found over the fracture surfaces beneath the blade tip.

Many of the HPT blades contained tip welding – a life extension procedure to repair the notching damage and rebuild the tip profile (figures 24 & 25). In the failed blade's case, the tip notching had intersected a rather large and deep tip weld repair and had subsequently propagated along this repair into the blade body, eventually growing beyond critical size and liberating the tip segment.



Figures 24 & 25. Polished and etched micro-sections showing the base metal (B), deep repair welds (D) and tip repair weld (T).

Why had the cracking propagated so rapidly along the weld repair, when other cracking from tip notches had not? The answer lay in the properties of the materials used. Investigation revealed the deep weld repairs were completed using a consumable with an inferior creep rupture, oxidation and fatigue resistance when compared with the blade base metal. The reason for the use of this material was the need to create sound, reproducible welds. The higher ductility of the selected filler material allows deep repairs to be carried out with a lower risk of defects induced by the welding process itself.

Normally, such areas were protected by a capping layer of a more resilient alloy, however once a tip crack had penetrated this and encountered a region of deep weld repairs, further propagation was promoted by the inferior properties of the weld material. Cracks entering these repairs were characterised by more rapid propagation and shortened time to failure. Indeed, it is likely that growth to failure may have occurred within a single inspection period.

Issues

This occurrence illustrates some of the issues that surround the repair and refurbishment of components. Each repair or modification carried out on an item irreversibly changes the nature of that component in ways that must be fully understood if the life and functionality of the item is to be preserved. In the same way that new component prototypes are rigorously tested to arrive upon a safe operating life, repaired components must also be evaluated for performance in a similar manner. Repaired components are rarely returned to as-new condition and as such, the effects of the repairs on the potential failure modes must be considered.

In this case, we have a premature failure that occurred as a product of a thermal fatigue cracking intersecting an area of repair work on the blade face. As the repair material was inferior to the base material in terms of its crack resistance, cracking propagated rapidly and blade failure resulted. In essence, the premature failure was a result of the repair/s carried out on the blade – thus indicating that blades repaired in this manner are inferior to new items in their resistance to this manner of failure.

In this case, it is important to consider one of a number of approaches:

- Allocate the repaired blades a lower life than their new counterparts, thus ensuring that any items that may be prone to failure in this way are removed from service before they fail.

- Increase the frequency of inspection of engines fitted with repaired blades.

- Re-design the repair (or the blade) to remove the susceptibility to failure in this manner.

Most importantly, however, is the need to adequately understand the potential behaviour of repaired components before they fail. If this is achieved, then it is possible to implement measures such as those above, without having to experience an in-service failure.