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Common failures in gas turbine blades

Tim J Carter *

P.O. Box 1535, Roosevelt Park, Johannesburg 2129, South Africa

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Abstract

Modern aviation gas turbine engines are considered to be highly reliable in that failures in service are rare. In fact this is a misconception, and freedom from service failures is largely the result of stringent standards imposed during frequent inspections. Most failures are thus detected at the incipient stage and appropriate action taken to prevent service failure. The common failure mechanisms found in gas turbine blades are discussed and illustrated.

Keywords: Aircraft failures; Engine failures; Turbine blade failures; Fatigue; Creep; Corrosion; Impact; Erosion

1. Introduction

Modern gas turbine engines for aviation applications are generally considered to exhibit a high level of reliability, and failure rates are considered low. In reality, this perception is incorrect, with component rejection for incipient failure symptoms during overhaul being fairly high. The situation is, however, controlled by the rigid inspection regime to which the engines are exposed, and the stringent criteria applied during inspections. Together, these ensure that almost all failures are detected at the incipient stage, and are removed from service for either replacement or refurbishment before failure actually occurs, leading to a low rate of actual failure in service.

The components most commonly rejected are the blades from both the compressor and the turbine (Fig. 1), and the turbine vanes. The reasons for this are fairly straightforward and are due to two principal causes, these being damage caused by ingested materials and damage due to the temperature of operation. Failures through mechanical mechanisms such as fatigue are rare, unless initiated by abnormal circumstances.

* Tel.: +27 11 782 7336.
E-mail address: timjcarter@lantic.net.

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Fig. 1. A typical high pressure gas turbine blade.

Blades from both compressor and turbine are subjected to some common conditions. Both are required to resist high mechanical loadings, imposed by both the high rotational speed which applies a large centrifugal load, and by aerodynamic forces, applied as a function of either the pressure rise through each stage of the compressor section, or of the pressure drop over each stage of the turbine. Both operate at temperatures different from ambient, in the case of the turbine blades and later stages of the compressor at higher temperatures and in the case of the first few rows of compressor blades at low temperatures, often as low as −50 °C.

In addition, the engine as a whole is subjected to weight restrictions. In order that the payload of the aircraft may be maximised, the weight of non-payload parts of the aircraft, such as engines, must be minimised. This is an important criterion, and one which plays a major role in the materials selection process for engine components where the most successful high-temperature resisting materials are nickel based alloys with a high density. An additional restriction on weight is imposed by the undesirability of a heavy disk/blade assembly rotating at high speed exerting a gyro effect on the handling characteristics of an aircraft during maneuvering in flight.

2. Mechanical damage

Any gas turbine engine ingests large amounts of air when in operation, either sucked in by the compressor or rammed in by the forward motion of the aircraft. In either event, any solid material entrained with the air will cause damage through either erosion or impact (Fig. 2). In most applications, filtration is not possible, although coarse screens to keep out the largest pieces are used in some applications.

To control the weight, the compressor blades are commonly manufactured from aluminium or titanium-based light alloys. Titanium alloys are commonly used in the higher pressure areas where the temperature, raised by both adiabatic and Joule–Kelvin heating is too high for longevity in high strength aluminium-based materials. Several engine designs use all-titanium blading in the compressor to give sufficient strength for high compression ratios with consequent high temperatures.

In some, mainly military, applications high-strength stainless steel alloys are used for the first row of compressor blades as a defence against ingested debris, known as ‘‘foreign object damage’’, generally referred to by its acronym FOD. In this case, the first row of blades are designed, in addition to their aerodynamic requirements, to be capable of ‘‘chopping-up’’ the bulk of the ingested material, rendering it fine

Fig. 2. Mechanical damage caused by ingested foreign material on the leading edge of a compressor blade.

enough to pass harmlessly through the remainder of the engine, without major damage to the blades themselves. This concept works well for larger, soft debris such as twigs or small birds, but is ineffective against the ingestion of fine abrasive material such as sand, which causes damage by abrasive wear to blades throughout the engine. Sand ingestion is a major problem with aircraft, especially helicopters, which operate from un-improved landing fields, such as are frequently found with aircraft working in humanitarian operations in third-world areas. Military aircraft operating from advanced theatre or "front-line" locations also experience similar problems with sand ingestion when landing or taking off. Some helicopters are fitted with cyclonic air filters on the intakes for use in desert conditions, where they are highly effective but costly in terms of engine performance and cannot be used if icing conditions may be encountered.

High-bypass ratio turbo-fan engines tend to experience low incidence of FOD damage to the core engine, since the fan blades throw ingested material outwards and into the bypass duct. The fan blades themselves, however, do suffer from impact damage.

Not surprisingly, the FOD problem is most common at low altitudes and tends to reduce at higher levels. Exceptions include ice, volcanic ash and birds, which can fly to surprisingly high altitudes. Vultures have been encountered riding rising air currents or "thermals" at well above 25,000 ft over Africa, and the highest recorded bird strike on an aircraft was with a vulture at 37,000 ft. The aircraft landed safely with one engine shut down. The vulture was less lucky. At least one aircraft is known by the writer to have been lost through ingestion of a plastic shopping bag, lifted to a significant altitude by a thermal. FOD ingestion at any altitude usually upsets the engine and may cause it to "flame-out" by initiating compressor stall. Relighting a turbine engine in flight after such an upset is by no means a certain operation and requires time for the engine to stabilise. In this case the attempts failed which, in a single-engine aircraft, could have only one outcome. Although the aircraft was destroyed, at least the pilot ejected safely.

Probably the most common source of FOD damage to compressor blades at high altitude is ice, formed on the air intake at the cold temperatures found at altitude. At altitude rain droplets are often found in a "super-cooled" state, still liquid but well below freezing point. Impact with the aircraft causes near-instant ice formation. Aircraft are normally fitted with de-icing systems to prevent accumulation of ice on aerodynamic surfaces and engine air intakes. These melt the ice, which passes harmlessly through the engine. If ice is allowed to form before the de-icing heaters on the intakes are activated, the ice can detach and enter the engine intake as solid ice rather than as water droplets. Airborne ice in the form of hail is often found at altitude. Against this the de-icing systems are ineffective and damage will result. The location of hailstorms is usually known, however, and aircraft routed away to prevent damage.

An uncommon form of FOD is volcanic ash, which can be found at high altitude after eruptions. The location of such ash clouds is normally known and avoided, but on at least two occasions, large passenger jets have accidentally flown into ash clouds with severe damage being inflicted on the engines as a result. Volcanic ash clouds also often contain high levels of sulphur which can cause corrosion damage, which will be dealt with later.

The most common cause of mechanical damage to blades is through the ingestion of solid material through the air intake. There have been many occurrences of the ingestion of hand tools accidentally left in or close to the air intake, and at least one instance where damage to an engine has been attributed to FOD through bird ingestion, which is normally covered by insurance, but which was compounded by the simultaneous ingestion of parts of the tree in which the bird was sitting, which is not.

The damage caused to compressor blades by FOD is mechanical, causing nicking and bending of the blades, even with "soft" FOD such as birds. This usually results in reduction of the fine balance of the system and degradation of the airflow characteristics over the blade aerofoil, leading to aerodynamically induced vibration or flutter, which initiates fatigue failures excited at rotation or blade passing frequencies. Parts of compressor blades breaking off in operation due to such damage can pass through the rest of the compressor, inevitably causing more damage. With most engine designs, however, such debris cannot enter the combustors, where the air is usually admitted through arrays of fine holes which serve to ensure both efficient combustion of the fuel and to protect the combustor chamber walls by providing a boundary layer of cooling air on the surface, and thus cannot damage the turbine.

3. High temperature damage

Whilst FOD affects compressor blades, turbine blades are subjected to a different damage regime. Unlike the compressor blades, which operate at relatively low temperatures but which may be exposed to ingested debris, the turbine blades operate in a largely debris-free environment. Foreign objects, by the time they reach the turbine, have been thoroughly minced by the compressor and incinerated by the combustion flame, and are unlikely to pose any mechanical threat, though the possibility of contamination leading to corrosion is present. An uncommon source of mechanical damage is erosion from carbon, deposited as coke around the fuel injection nozzles when the spray pattern of the nozzle is degraded, passing through the turbine. Similarly, particles of ceramic thermal barrier coatings, often applied to the combustion chamber surfaces to assist with keeping the walls cool, detaching due to thermal shock and passing through the downstream parts of the engine.

4. High temperature exposure

The turbine blades operate at elevated temperatures at the very edge of metallurgical alloy development. Three probable damage mechanisms affect turbine blades, these being mechanical damage through either creep or fatigue and high temperature corrosion.

The use of light alloys for the high temperature sections of the engine is not feasible since they cannot generally be designed to give acceptable creep properties at the high temperatures needed for efficient turbine operation. In the case of aluminium alloys, the operating temperature is above the melting point. For the most part, nickel base alloys are used and the weight penalty is accepted. The use of hollow blades, sometimes with air ducted through the interior for cooling, reduces blade weight. The most common materials for turbine blade manufacture are the nickel-based "super-alloy" materials. Used as both forgings and, more popularly for blades as castings, these alloys are able to withstand the very aggressive environment of high temperature and high stress found within the hot gas path of a turbine engine. Nickel is considered as a most suitable basis for alloying since it exhibits, by virtue of its almost-full third electron shell, a high capacity for forming stable alloys without phase instability. It also forms, with chromium additions, Cr_2O_3-rich surface oxide films, which are both stable and protective, restricting movement of both metallic elements in the outward direction, and aggressive atmospheric elements such as oxygen, nitrogen and sulphur in an inward direction. Nickel will also form, with aluminium additions, Al_2O_3 surface layers, which are highly oxidation-resistant at very high temperatures.

Nickel-base alloy turbine blade materials are immensely complicated in terms of microstructure, with the efforts of alloy developers over the years having created a range of fine precipitates which confer high levels of resistance to creep. The basic alloys are almost all based on an FCC γ-phase nickel continuum, with additions such as chromium to confer oxidation resistance, into which is precipitated a γ' second phase (Fig. 3) with the general form $Ni(Al,Ti)_3$ formed through alloying with aluminium and titanium. The γ' phase shows an unusual property in that it tends to increase in strength with increasing temperature, at least at lower temperatures below about 973 °K. This is significant when the second phase is in excess of 50%, as is often the case with high temperature nickel alloys.

The precipitation of the γ' phase is carefully controlled during manufacture to give a controlled size and morphology, resulting in a fine, ordered quasi-cubic precipitate (Fig. 3) to optimise high temperature strength by maximising resistance to both diffusion creep at lower temperatures and power-law creep at higher temperatures. This structure, whilst effective in controlling creep, can be modified by exposure to stress at high temperature which results in the cubic particles growing into plate-like "rafts" oriented perpendicularly to the applied stress (Fig. 3). This "rafted" structure results in a degraded performance in diffusion creep at moderately elevated temperatures. Since the lenticular shape of the γ' precipitate in a rafted structure tends to inhibit dislocation climb when compared to the same movement around cubic γ', a rafted structure presents a slight improvement in creep performance at higher temperatures. In real terms, however, this benefit is minimal and must be offset against the diminution of creep strength at more normal operating temperatures. If the exposure to elevated temperatures continues, the rafted structure further degrades, by an Ostwald ripening mechanism, to form large particles with a shape tending towards spherical. As the temperature approaches the γ' solvus, the γ' phase dissolves into the γ continuum and the particle size first reduces and finally disappears. As the γ' phase dissolves, the material strength in creep diminishes. If the blade is allowed to continue in service in this condition, failure by creep is very probable, with consequent destruction or serious damage to the engine.

Under normal conditions, blades should never be operated at excessive temperatures for long enough periods to cause microstructural damage. Some elevated temperature exposure is permitted for very limited periods, for example during start or for emergency situations. Such exposure should be strictly controlled, with inspection for possible damage, including metallographic examination of sample blades, being required. Once the microstructure has been degraded by exposure to elevated temperature, it is normally assumed that the blades have been damaged and replacement is mandatory. If the solutioned microstructure is permitted to remain in service, perhaps as a result of the high temperature excursion going undetected, the dissolved phase will re-precipitate during normal operation (Fig. 3). Since the temperature conditions within the engine in normal operation are, for obvious reasons, lower than those required to produce the desired γ' particle size and morphology, the re-precipitated material does not re-gain its original properties.

5. Creep failures

All turbine blades and sometimes the high pressure stages of compressor blades are subject to creep as a natural consequence of operating at high temperatures and stresses, and creep is eventually the life-limiting process for all blades so exposed. In normal service, creep manifests itself as blade "stretch" in which the blade elongates in service. In abnormal conditions, this may be sufficient for the blade tip to contact the

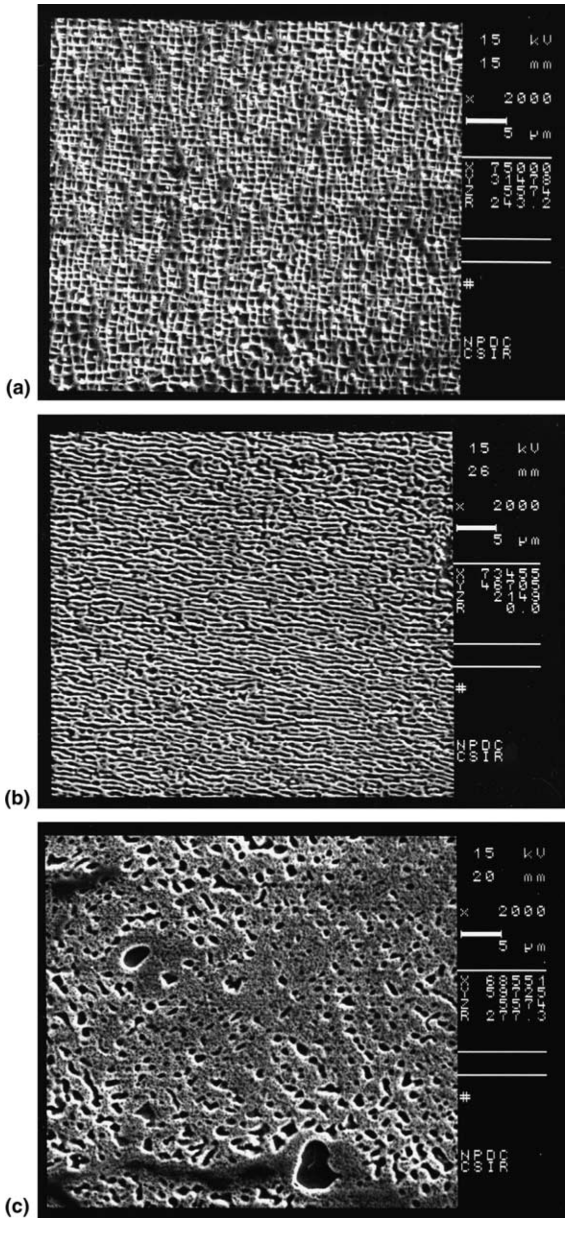


Fig. 3. Typical microstructures of blade materials in various states: (a) an undamaged structure of γ' quasi-cuboids; (b) rafted γ' resulting from exposure to stress at high temperature; (c) solutioned and re-precipitated γ' from extreme temperature exposure and subsequent operation.

non-rotating shroud, causing a "tip rub" which necessitates dismantling of the engine for repair and quite probably replacement of both blades and shroud. Blade stretch is measured routinely during inspections and the length trimmed to restore the correct tip clearance. The blade is discarded when the accumulated strain reaches a pre-determined value. This procedure is designed to prevent creep failures and, provided that the engine is operated within normal limits, is successful. Blades do fail by creep when the operating temperatures of the engine are exceeded for more than brief periods or when the inspection procedures are not correctly followed. The appearance of creep in turbine blades can be confusing if the structure of the blade is not recognised, Creep cracking in a blade having a directionally solidified (DX) structure

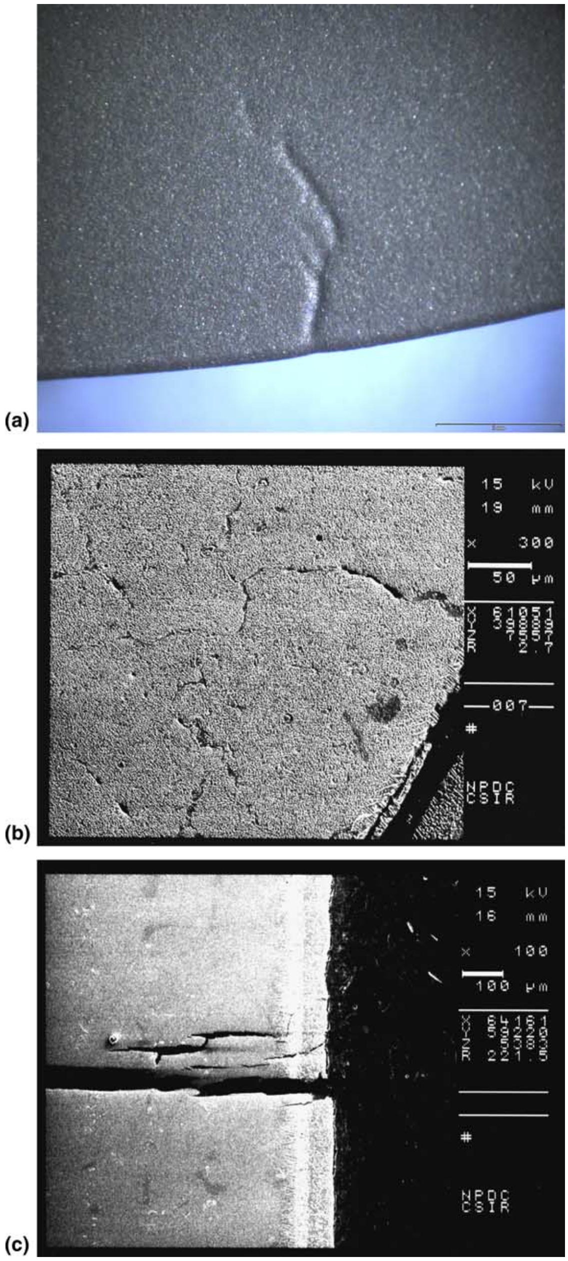


Fig. 4. (a) Creep damage observed during routine inspection; (b) grain boundary separation found on metallographic examination of the same blade; (c) appearance of creep cracking in a directionally solidified blade material.

can appear metallographically different from that found in a more conventional polycrystalline component (Fig. 4).

6. Fatigue failures

High cycle fatigue (HCF) failures are rare in gas turbine rotating parts, unless some form of initiating damage, such as FOD from ingested debris has been inflicted or where a manufacturing defect is present (Fig. 5). Gas turbine blades are carefully designed to avoid HCF, since they accumulate stress cycles at a prodigious rate.

If we consider a turbine rotating at 35,000 rpm, by no means an unusually high speed, any imbalance in the rotor will apply stress cycles at a rate of 2.1×10^6 cycles per operating hour. This is sufficient to reach 10^9 cycles, accepted in general engineering as the demarcation point for acceptable performance in a system exposed to fatigue conditions, in less than 500 h.

If we examine the various harmonic frequencies at which the rotor will accumulate stress cycles, such as blade passing frequencies, the numbers approach the astronomic. If we consider the disk already considered, which spins at 35,000 rpm, and add that it carries 59 blades, and rotates in front of a static vane ring having 19 vanes, we arrive at two blade passing frequencies. It is of interest to note that both 19 and 59 are

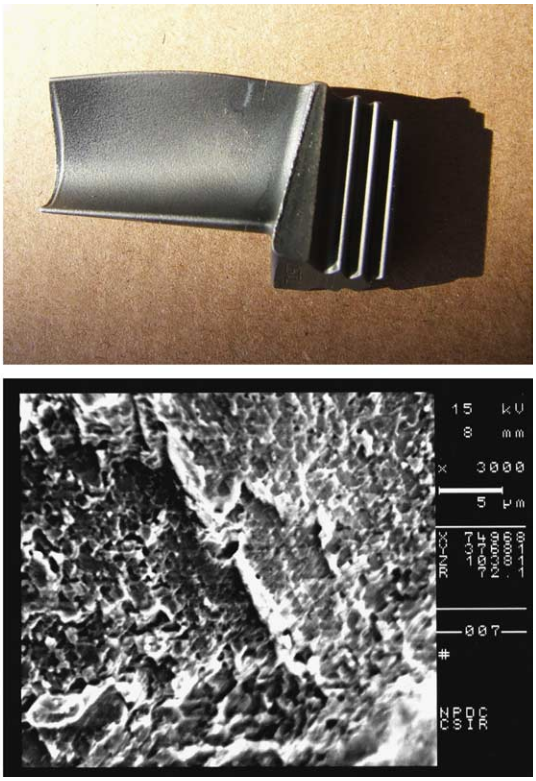
(a)
(b)


Fig. 5. Fatigue cracking, initiating at metallurgical defect, found in trailing edge of blade to the right of the pencil mark, and SEM image of crack surface showing striations, confirming the fatigue mechanism.

prime numbers. This is deliberate, prime numbers of blades and vanes are often selected to reduce the harmonics available to an engine in operation and any harmonics which are present are designed to occur at frequencies as far from the normal operating condition as possible. Harmonics may well be encountered during start or shut-down, they manifest as a slight vibration as the engine spools up or down. Looking at blade passing frequencies at 35,000 rpm, we come to 12.4×10^7 cycles per operating hour for the rotating blade, and at 39.9×10^6 cycles per operating hour for the vane. These rates are far in excess of any acceptable value for any structure susceptible to fatigue which has to have a sensibly long operating life.

How long that life needs to be to be "sensible" depends on the intended use of the equipment. The Saturn V booster, used to send men to the moon when we still did such things, had a fatigue life, primarily due to acoustic excitation of the structure when all engines were operating at full power during lift-off, of just 120 s. This did not matter very much, since the fuel was expended in less than 90 s, giving an acceptable safety margin, but did make the recovery of the vehicle for re-use somewhat pointless. Every Saturn V which was successfully launched now lies at the bottom of the Atlantic after just 90 s of operation.

Gas turbine engines for aviation applications quite normally operate to 2000 h before inspection of the turbine, and often over 5000 h before overhaul. Ground-power or marine applications can operate for considerably longer periods. Even then, the blades would normally be cleaned, checked, and re-used, with replacement only if damage such as excessive stretching due to creep, tip rubbing or evidence of overheat damage was found.

The fact remains that the modern gas turbine engine has had fatigue virtually eliminated at the design stage, and high cycle fatigue without external initiation is a most unusual failure mode. Any form of external damage resulting in a notch-like defect, such as a nick or dent will, however, result in a near-instant failure by fatigue due to the very high rate of cycle imposition resulting from the speed of rotation and higher frequencies such as blade passing frequencies.

Low cycle fatigue (LCF) is a different matter. Related to the much larger stress cycles imposed by starting and stopping in operation, LCF is the main reason for cycle limitations on component life. The source of these stresses is fairly apparent. When stopped, the disk/blade combination is subjected to loadings mainly due to self-weight, and is cold or at least at room temperature. In operation, the same components are subjected to large, though fairly constant loadings from centrifugal forges imposed by the rotational speed, and are at a much higher temperature. The rate of change between these two states is rapid on engine start, inducing high levels of thermal stress, which reduce to a steady state during operation and then reappear, in reverse, during cool-down. The disks which hold the blades in an engine are commonly life limited by the number of stop/start cycles to which they are subjected in service, rather than by the hours of service. This rate varies considerably depending on the engine, and is determined largely by the size of the loadings imposed and the temperatures to which the disk is exposed. A small, high speed disk in the high temperature stages of an engine might be limited to about 10,000 cycles or less, whilst disks in cooler parts of the same engine might be permitted to continue to 20,000 cycles or even more. Disks in larger engines, which have slower rotation speeds but often larger blades, giving similar loadings may be similarly lifed. Additionally, thermal stresses, due to the blades heating more quickly than the disk and surrounding shroud, on start-up and cooling more quickly on shut-down add to the LCF loadings. An aircraft flying short journeys may reach the end of the disk life in as little as five years whereas a big jet flying long intercontinental journeys may well reach the fatigue life limit for airframe before the cycle limit for the engine disks.

One example, a Boeing 747-244 aircraft spent its entire life from delivery to the airline to retirement to a museum with one airline, and for which, therefore, accurate records are available, flew a total of 107,000 h and 20,291 cycles over a life of more than 30 years without serious incident. The engines were removed for further use after the aircraft was placed in the museum. Over that life, the engines no doubt had blades replaced, but it is believed that the disks would still be original.

7. Corrosion failures

Both compressor and turbine blades are exposed to aggressively corrosive conditions (Fig. 6). The ingested air may well contain sodium and chlorine, in the form of salt from sea air or from runway de-icing treatments or marine environments. Atmospheric contaminants result from natural sources, such as marine environments or through pollution from industry or forest fires, and usually contain sulphur and sodium as the most active elements. Volcanic activity can generate significant levels of pollutants, particularly sulphur.

The turbine blades are exposed to strongly oxidising conditions and the gaseous combustion products contain elements such as sulphur, vanadium or even lead and bromine from the fuel at very high temperatures.

The sources of these fuel contaminants deserves some explanation. Lead and bromine are not usually added to the kerosine used for aviation fuel in its several variants, but are almost invariably found in aviation gasoline or "avgas" designed for use in reciprocating engines. Liquid fueled gas turbines are, on the whole, tolerant of a wide range of fuels, and it is by no means uncommon for the permitted fuels to include, when normal aviation turbine kerosine is unavailable, gasoline, either as avgas or, with greater restrictions, motor gasoline (mogas). Both of these fuels contain tetra-ethyl lead as an octane improver to prevent pre-ignition in a piston engine, and also ethyl bromide as an additive to promote dispersion of the lead after it has served its purpose. Because these fuels contain these ingredients which are harmful to turbine blade materials, their use is generally restricted to an "only when necessary" basis and then for a limited period, after which inspection for possible damage is mandated. Military engines, which can easily require re-fueling with whatever happens to be available in the theatre where they are situated are really a different case, in that their combat life may well be less than the engine life. At least one military aviation engine is certified for fuels ranging from straight-run gas oil through diesoline and illuminating paraffin to aviation gasoline. Ground-based turbines commonly operate on a wide variety of fuels with, in general, higher levels of contaminants than aviation fuels.

Any of these will attack the nickel based alloys from which turbine blades are manufactured very readily at elevated temperatures, and sophisticated coatings are employed to protect the blade material. Oxidation from excess air entering the combustion system will also attack an unprotected nickel alloy blade.

Turbine blades are normally protected with sophisticated coatings, usually based on chromium and aluminium, but often containing exotic elements such as yttrium and platinum group metals to provide resistance to corrosion and oxidation in service. Attack is, however, inevitable if the engine is operated in a sufficiently contaminated environment, either through atmospheric contamination or the presence of excessive quantities of harmful elements in the fuel.

Fig. 6. Sulphidation attack of a turbine blade. Such damage can sometimes be repaired by removing the damaged coating and re-applying a new coating.

Corrosion damage to compressor blades occurs mainly through ingested atmospheric pollutants mixing with the water vapour inevitably present. Whilst this can cause corrosion during operation, a much more prevalent attack is caused by aggressive atmospheric conditions whilst that engine is standing, particularly in marine environments. This damage is normally reduced by frequent "compressor wash" treatment, in which water, together with appropriate detergents, is introduced into the intake airstream of an operating engine. The correct amount of water, sufficient to wash deposits from the blade surfaces, is insufficient to quench the combustion chamber flame, and is an efficient means of cleaning corrosive atmospheric deposits from the compressor surfaces. This reduces the corrosion load on the compressor blades and vanes, and improves aerodynamic efficiency, albeit with a risk of not washing the material completely through the engine and leaving deposits on the turbine. Such corrosive material would, however, inevitably travel through the engine in service and contaminate the turbine, and compressor washing is widely recognised as a beneficial treatment in the alleviation of corrosion through ingested corrodants. In conditions which are considered "difficult", such as short range operation in marine environments, this treatment may be carried out every day. Fitting of protective plugs to the air intake and exhaust to limit the ingress of environmental air during idle periods is normal, and specific corrosion inhibition practices are specified for prolonged periods of non-operation.

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