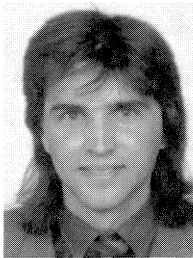# FAILURE OF TURBOMACHINERY COMPONENTS

by

Paul Lowden

Metallurgist

and

Joseph Liburdi

President

Liburdi Engineering, Limited

Burlington, Ontario, Canada

Paul Lowden received his B.Eng. degree in Metallurgy from McMaster University in 1981. After graduation, he joined Liburdi Engineering, Limited, where he has been involved with the failure analysis of a wide variety of turbine components. In addition, he has been responsible for providing metallurgical support for the firm's blade repair facilities and for the development of advanced repair techniques.

Joseph Liburdi graduated in 1967 from the University of Windsor with a B.S. degree in Engineering Materials. After graduation, he joined Westinghouse Canada, where, as Manager of the Metallurgical Section, he was responsible for the metallurgical support to the gas and steam turbine departments, as well as for HIP process development.

In 1979, he established Liburdi Engineering Limited, which specializes in engineering analysis and blade repairs for the turbine industry.

ABSTRACT

The analysis of turbomachinery failures is a highly specialized field requiring a detailed understanding of superalloy metallurgy, moderate and high temperature failure mechanisms and an appreciation of the stresses, excitations and mechanical design characteristics of the various parts. Common failure mechanisms such as creep, fatigue, oxidation, corrosion, and wear are often observed, either singly or in combination, which makes the identification of the primary mode of failure more complex. To assist with the identification of service failures, a review of the principal failure mechanisms is presented along with the associated metallurgical features. In addition, a number of cases are presented to emphasize the need for a cooperative approach to failure analysis in order to translate the metallurgical information to possible mechanical/operational causes and solutions.

INTRODUCTION

Failures in turbomachinery components are often complex in nature and require a detailed understanding of not only metallurgy, but also mechanical design, inspection techniques, overhaul practices and operational characteristics. The analysis of failures should determine the prime causes and identify solutions or steps which could be taken to reduce the probability of future recurrences.

During the investigation of a failure, the metallurgist, the design engineer and the operator must pool their resources and expertise to extract the maximum information from the event. The metallurgist will examine the fractures with the aid of electron optics and determine where the failure started, the mechanism of crack growth and whether there were any material deficiencies. The mechanical engineer must examine the design and relate the location and mode of failure to stress patterns or vibrational frequency response. The operator must review all engine records for clues leading to the incident and ensure that the theory of failure is consistent with the events.

In order to illustrate this interactive process, a number of cases are presented. The failures have been chosen from the principal components of various turbines and provide a representative cross-section of the mechanisms and failure modes that can be encountered in service.

FAILURE MECHANISMS

The first task of the metallurgist is to sift through the wrecked or cracked components looking for the piece that started the event, so that the laboratory analysis can be performed on the most significant (representative) fractures. This is often accomplished by visually reviewing both the overall appearance of the wreck as well as examining individual pieces for evidence of prior cracking (Figure 1).

Figure 1. Blade Root Section (Identified by the Arrow) Chosen for Analysis Due to Its Discoloration. This blade was found to have failed in creep, causing the remainder of the damage.

The failed components can be transferred to the laboratory where a more detailed inspection is performed using a high sensitivity penetrant to detect any hidden or secondary cracks. Selected fractures are prepared and examined, using increasing levels of magnification, from the optical stereo microscope to the electron microscope, to ensure that all possible information is extracted. At the same time, the material chemistry, microstructure and mechanical properties are checked and compared to specification requirements.

The following sections outline the features of the primary modes of failure.

Creep

Creep failures occur primarily in hot section components as the result of continued exposure to high temperatures and stresses during operation. Some amount of creep is normally expected in highly stressed components, such as blades and discs, and such components are said to be creep life limited. Generally, these limits are based on the extrapolation of short-term creep data to estimate the expected life at operating conditions. However, actual engine conditions can, in some cases, cause creep failures well in advance of the predicted life.

At the stress and temperature levels encountered in the hot section of gas turbines, creep failure occurs by the accumulation of damage along grain boundaries in the form of microscopic voids. Such voids can be detected by optical microscopy only in the most advanced stages of creep. In the final stages of a creep failure, these voids link together to form an intergranular crack which can grow to a critical size and result in a catastrophic failure. The accumulation and growth of voids can occur throughout the material, or in a localized manner at the tip of the advancing creep crack, depending on whether the driving force for the crack is the stress concentration at the crack tip or the net section stress.

A creep crack which has grown to failure generally exhibits at least two distinct regions corresponding to the initial creep crack and the final overload zone. Optically, the creep region is characteristically discolored by oxidation, while the overload zone has a bright metallic appearance (Figure 2). More detailed examination by a scanning electron microscope (SEM) clearly reveals the intergranular nature of the cracks and, in many cases, grain boundary voids which have not linked to the crack are evident at the edge of the creep zone (Figures 3 and 4). The voids will grow and link to the crack.

Figure 3. Creep Region of the Fracture Shown in Figure 2, Illustrating the Intergranular Nature of Creep Crack Growth.
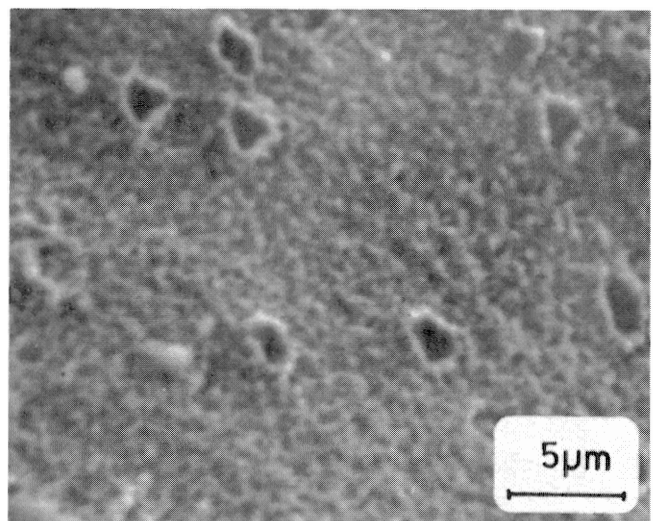
Figure 4. Voids Just Ahead of the Main Creep Crack in Figure 2.

The formation and intergranular crack growth can also be identified in metallographic cross-sections removed through the crack or fracture (Figures 5 and 6). The cross-sections may also reveal the presence of multiple branching cracks running parallel to the main crack or fracture, which is another typical feature of creep cracking (Figure 5).

Creep failures are often accelerated by, or in extreme cases, even caused by overaging of the alloy microstructure. The precipitation hardened alloys used for the highly stressed hot section components are strengthened by second phase gamma prime particles. At the high operating temperatures of these components, the gamma prime particles can grow well beyond the optimal size present in the new components (Figure 7). The strengthening gamma prime particles in the service exposed material can change considerably with exposure. The large particles may become rounded and grow at the expense of the smaller particles, resulting in a measured decrease in the creep rupture life to as low as five percent of the normal test requirement. This can result in dramatic decreases in the creep resistance of the alloy and thus accelerate the accumulation of creep damage. Due to the extremely fine size of the gamma prime particles, such effects can only be detected through use of the transmission electron microscope (TEM).
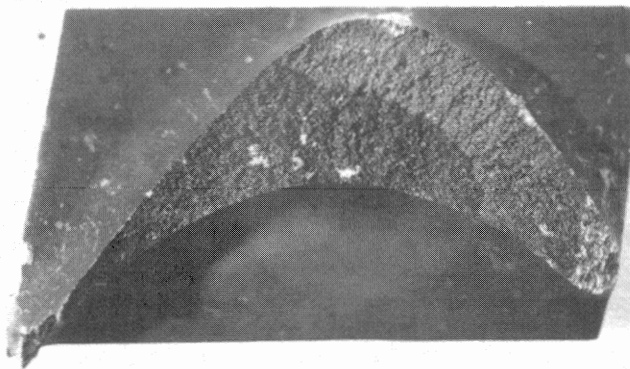

Figure 2. Fractured Blade from the Wreck Shown in Figure 1 After Cleaning. The original creep crack area is clearly marked by discoloration caused by oxidation. The lighter region of the surface is the final fracture zone which failed by tensile overload.
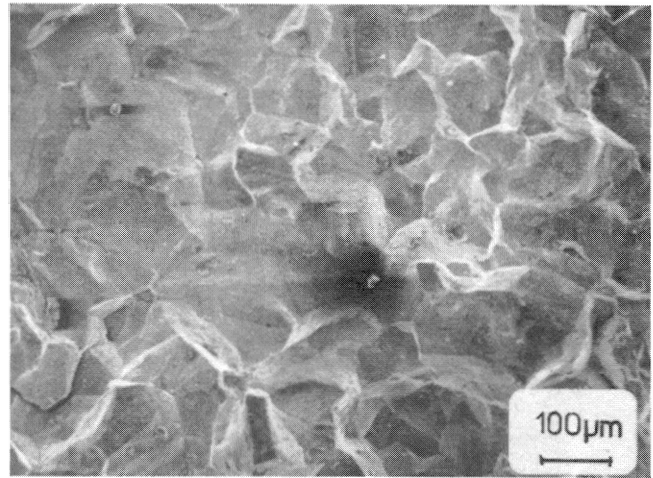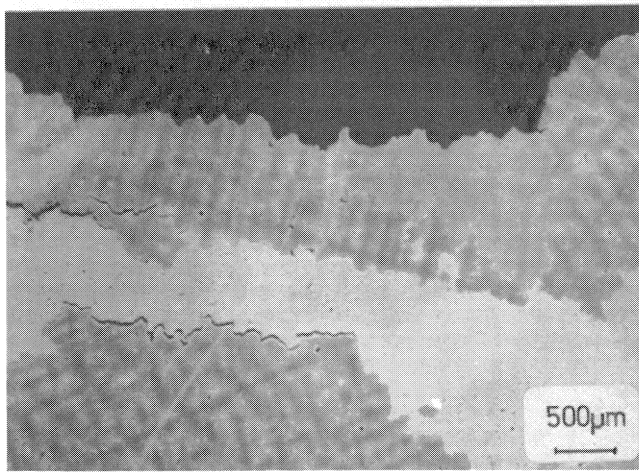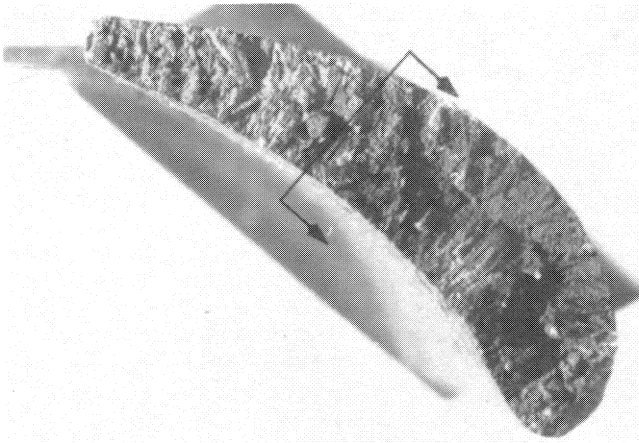
Figure 5. Photomicrograph of a Creep Fracture in a Cast IN738 Alloy Industrial Turbine Blade. The intergranular nature of the main fracture is clearly evident. The small secondary cracks running parallel to the main fracture are also intergranular creep cracks.
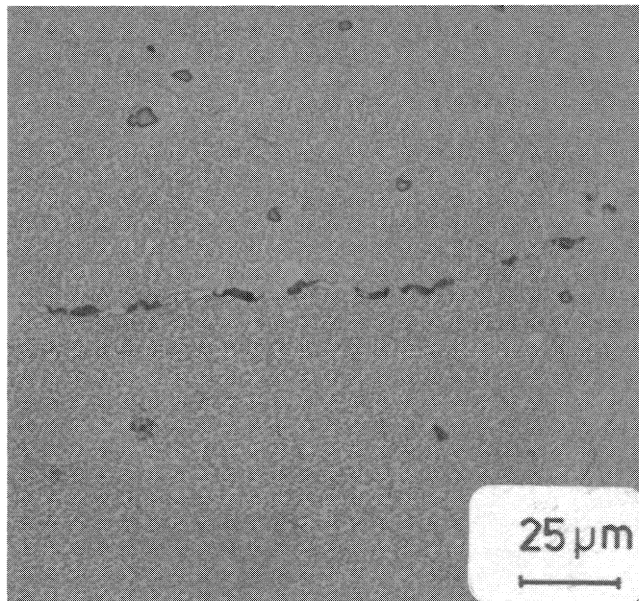

Figure 6. Photomicrograph of Intergranular Creep Cavitation Which Was Found on Grain Boundaries in the Cast Turbine Blade Failure Shown in Figure 5.
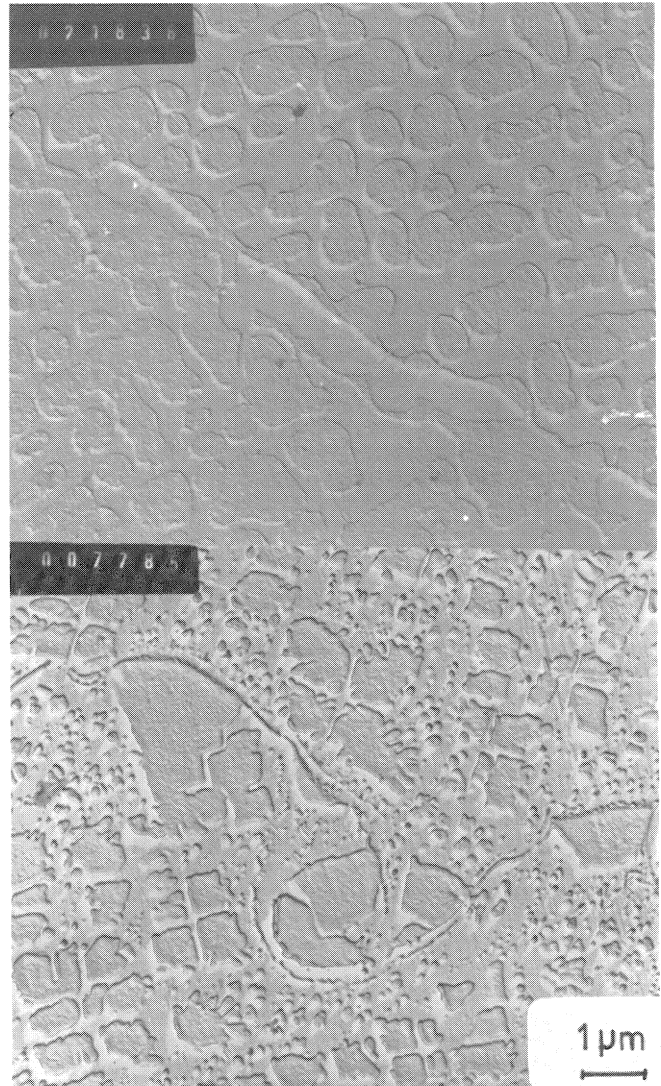

Figure 7. TEM Photomicrographs Showing the Effect of Extended High Temperature Exposure. The top microstructure is from the failed blade shown in Figures 5 and 6 which had been in service for 30,000 hours. The bottom microstructure is from a new IN738 turbine blade.

Fatigue

Fatigue failures occur as the result of the application of repetitive or fluctuating stresses at levels generally much lower than the (single load) tensile strength of the material. Unlike creep, fatigue is not strongly influenced by temperature. Thus, fatigue can occur in both hot and cold section components.

Fatigue failures are generally categorized as occurring by either high cycle or low cycle mechanisms, depending on the frequency of the loading. Typically, low cycle fatigue occurs as the result of stresses applied once per engine operation cycle, such as those resulting from differential thermal expansion of gas path components during startup and shutdown. In such cases, the stress levels required to initiate and propagate a crack are generally of the order of the yield stress. High cycle fatigue occurs at much higher frequencies associated with machine vibrations and aerodynamic effects and the fluctuating stresses are much lower. At such high frequencies, resonance of the component with the applied cyclic stress becomes an important factor since it acts to increase the maximum stresses experienced by the part. As would be expected, the

differences in the loading conditions for high and low cycle fatigue result in different crack growth mechanisms and fracture appearances.

Depending on the temperature range, low cycle fatigue damage can accumulate primarily by plastic deformation or by the combination of plastic and creep deformation at higher temperatures. High temperature low cycle fatigue cracks are therefore very similar in appearance to creep cracks, featuring both an intergranular fracture path and the presence of intergranular voids (Figures 8 and 9). They can be distinguished from creep cracks both by their locations in areas where steady state stresses are low and by the typically larger and more numerous voids present. In a number of failures, it is likely that the combined effects of steady state creep stresses and superimposed low cycle fatigue stresses act to propagate the crack. At lower temperatures and higher strains where plastic deformation dominates, transgranular crack propagation occurs.
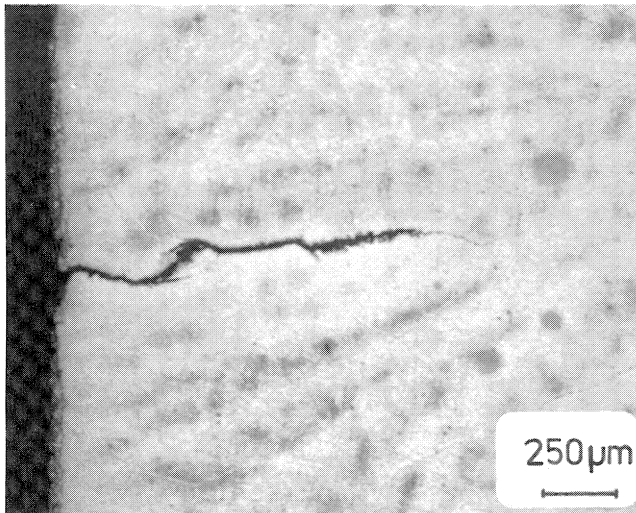

Figure 8. *Photomicrograph of a High Temperature, Low Cycle Fatigue Crack Which Has Propagated in a Stationary Turbine Vane. The intergranular crack path is due to the strong creep component of the cyclic deformation at high temperature resulting in a creep-like crack.*
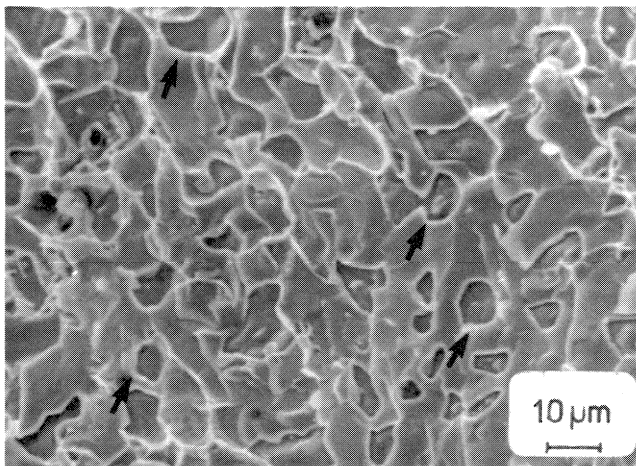

Figure 9. *SEM Fractograph of Voids Formed by High Temperature, Low Cycle Fatigue in the Cracked Vanes Shown in Figure 8. The cavities are generally larger and more numerous than those formed by pure creep mechanisms, allowing the two modes of failure to be distinguished.*

In high cycle fatigue, elastic deformation predominates in all temperature regimes. The cracks, therefore, generally initiate and propagate along a transgranular path, giving the fracture a characteristically smooth appearance. A notable feature of many fatigue fractures is the presence of clam-shaped "beach marks" which mark the progress of the crack at various stages of its life (Figure 10). These marks are formed by changes in the level of oxidation due to temporary halts in the crack growth as loading or fatigue excitation changes, thus forming a concentric pattern around the crack initiation. SEM examination of fatigue fracture surfaces often reveals the presence of fine striations running perpendicular to the crack direction (Figure 11). Each of these striations marks the advancement of the crack during one loading cycle. Thus, the spacing of striations can be used, in certain instances, to estimate the rate of crack growth.
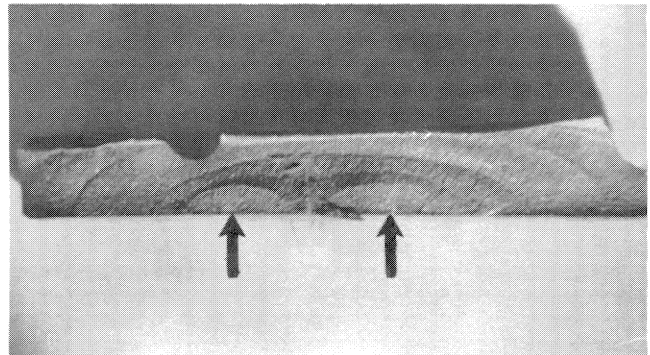

Figure 10. *Typical Clam Shaped "Beach Marks" on the Fracture Surface of a Fatigue Crack through an Industrial Turbine Disc. Two cracks appear to have initiated (arrows) and grown together.*
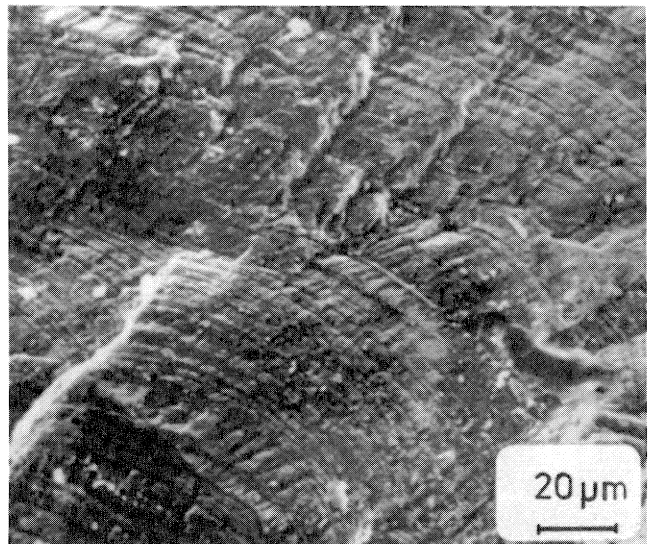

Figure 11. *SEM Fractograph of Fatigue Striations on the Fracture Surface of a Failed Turbine Blade. The striations are formed perpendicular to the direction of propagation, marking the movement of the fracture front in each stress cycle.*

Environmental Attack

A wide variety of failure mechanisms involve the interaction of turbine components with the operating environment. In particular, hot section components are subject to high temperature oxidation, sulphidation and corrosion by the combustion gases. Although such failures seldom lead directly to the

catastrophic wreck of an engine, they can be expensive in terms of part replacement rate and loss of efficiency and, in severe cases, may be a factor in more damaging failures resulting from other mechanisms.

In the superalloys used in modern turbines, a continuous self-healing layer of aluminum, chromium and/or silicon oxides is formed by the reaction of oxygen with these elements contained in the alloy. This layer protects the alloy by retarding further reactions between the components of the combustion gas and the alloy. The effectiveness of the protective oxide layer in clean gas is limited primarily by temperature. As temperature increases, the rate of reactions occurring through the oxide increases to the point where appreciable reaction with the alloy can occur. This results in the depletion of those elements required to form the protective layer and occurs at a greatly accelerated rate.

Sulphidation and hot corrosion are related phenomena which attack the alloy by interfering with the function of the protective oxide layer. Sulphidation occurs by the reaction of sulphur (from fuel contamination) with the alloy, which depletes the elements that normally form the protective oxide. Hot corrosion occurs by the interaction of the surface layer with contaminants in the fuel, such as sodium sulphate, which together form a non-protective liquid layer allowing severe base metal attack to occur.

The external appearance of hot section components which have failed by the various mechanisms described is similar. Thus, to determine by what mechanism a given hot section failure has occurred, it is often necessary to perform a detailed metallographic analysis. In general, the appearance of the phases present at the component surface can be used to identify the mode of attack. However, in some instances, it is necessary to use micro-analysis techniques, such as energy dispersive spectroscopy on the SEM, to identify specific contaminants. Sulphidation and oxidation failures both result in the formation of internal phases. However, the sulphides formed by the sulphidation mechanism have a characteristic light gray coloring and globular appearance which distinguishes them from the crystalline oxides (Figures 12 and 13). Hot corrosion can exhibit characteristics of both sulphidation and oxidation, in addition to the characteristic presence of a heavy scale on the surface.
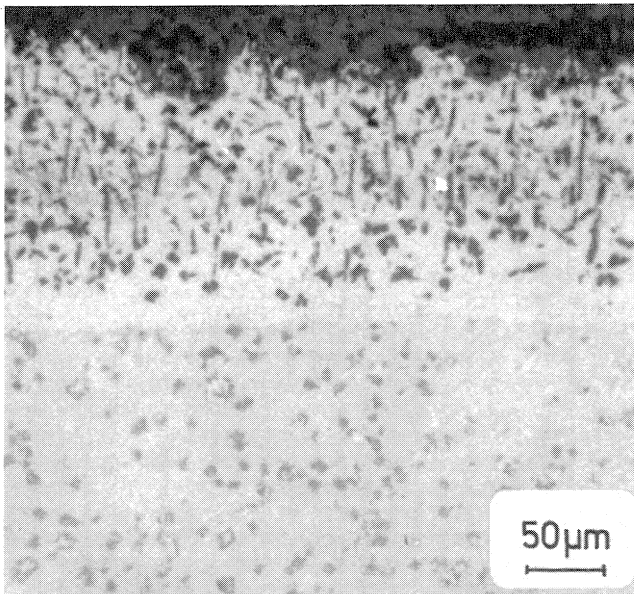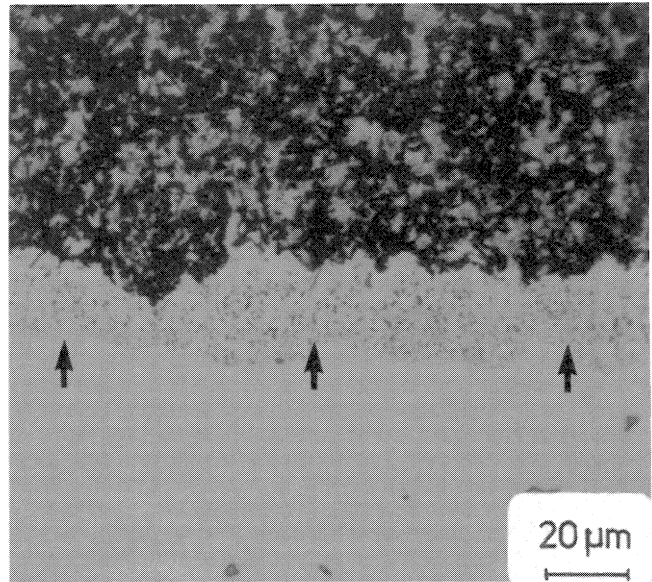

Figure 13. Photomicrograph Indicating the Sulphidation Attack of a Turbine Blade. Sulphur in the fuel reacted with the base metal to form the small globular sulphide particles evident in a band just below the scale. The reaction depletes the alloy of the elements required to form a protective oxide layer, thereby allowing oxidation to advance into the component as evidenced by the thick band of dark crystalline oxide which has formed.

To help prevent such failures, coatings with improved environmental resistance have been developed for application to turbine components. These coatings form a protective oxide layer similar to that formed on the base alloys. However, by having a higher concentration of the oxide forming elements, such coatings are able to exhibit superior oxidation and corrosion resistance.

All of the environmental and mechanical failure mechanisms applicable to the base metal can also occur in coatings. Cracking of the coating is of great concern, since it can cause accelerated attack of the corrosion spikes as well as act as notches or stress risers. Such failures are, in the majority of cases, caused by impact or thermal fatigue, resulting in the formation of crack networks through the brittle coating. The type of cracking can be determined from the pattern of the network. Impact cracks exhibit a concentric pattern radiating from the point of impact, while fatigue cracking occurs in a regular pattern outlining the maximum tensile stresses developed by the thermal mismatch between the coating and the base metal (Figures 14 and 15). The failure of the coating by either mechanical or environmental mechanisms can result in severe attack of the base metal, since coatings are normally used to protect or increase the corrosion resistance of the base metal (Figure 16).

Erosion and Wear

Erosion and wear damage, like environmental failures, are seldom the direct cause of catastrophic failures. Nevertheless, they are costly, due to frequent overhaul and replacement of components and the degradation of performance. It is also possible for erosion or wear to weaken the parts and cause their eventual failure by other more damaging mechanisms. Both cold and hot components are subject to such failures, since the mechanisms are largely temperature independent.

Wear failures are caused by the relative motion of two adjacent parts, which are in continuous or intermittent contact.

Figure 12. Photomicrograph Demonstrating the Oxidation Attack of a Turbine Blade.
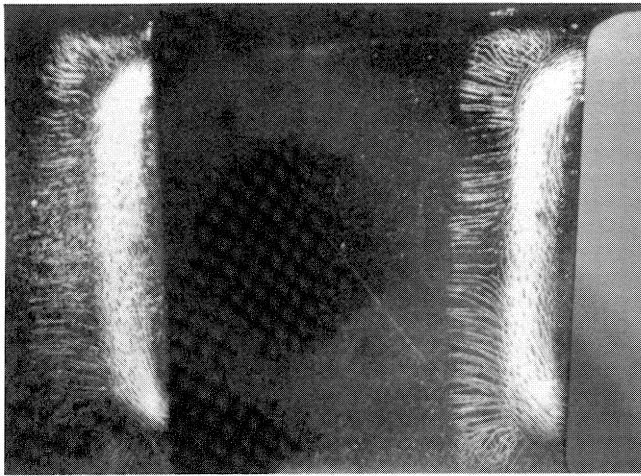
Figure 14. Pattern of Fine Cracks Found in the Coating of a Turbine Vane Segment as Revealed by Fluorescent Penetrant Inspection. The crack pattern is typical of thermal restraint cracking arising from rapid cycling and the difference of expansion coefficients between the coating and the base material.
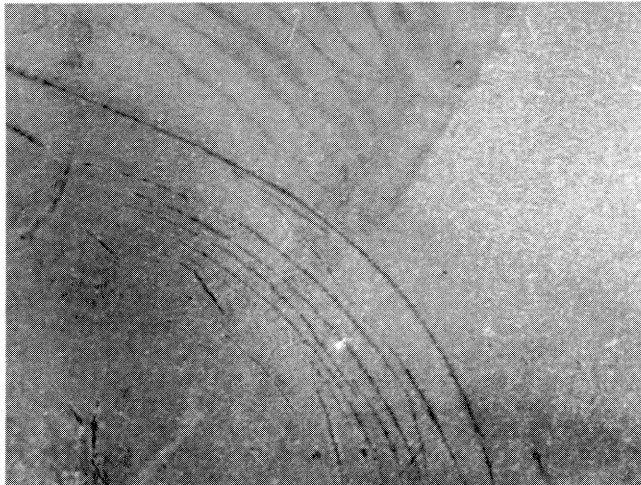

Figure 15. Typical Impact Damage Cracks in a Turbine Blade. The cracks form due to the poor ductility of the coatings.
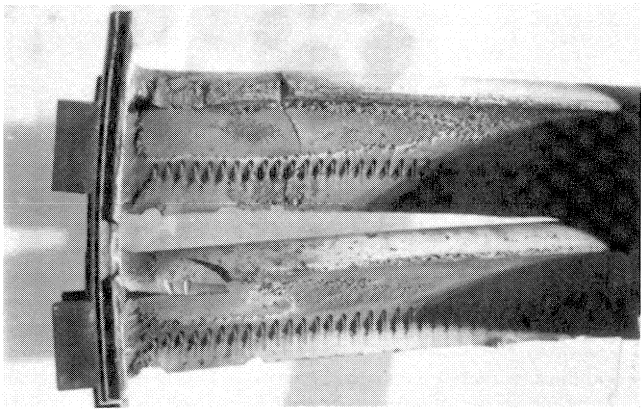

Figure 16. Severe Sulphidation Attack Which Resulted in Turbine Vane Segment Fracture After the Failure of a Protective Aluminide Coating in a Sour Gas Environment. Due to the severe loss of metal thickness from the environmental attack, some thermal fatigue cracks have also formed.

The magnitude of the motion can range from the extremely high speed of a rotating part contacting a non-rotating part to that occurring between two essentially stationary parts by vibration. In general, the wear is fairly evenly distributed between the two components and, thus, the parts which are rubbing can be identified.

Erosion failures occur by the contact of particles contained in the inlet air with components in the gas path and can result in significant changes in airfoil geometries. Erosion rates are dependent on the velocity and impingement angle, with the maximum rates occurring at 90° and approximately 30°. This results in a characteristic erosion pattern, with the most severe attack at the leading edge and trailing edge concave sides of the airfoils, where the impingement angle are approximately 90° and 30°, respectively. Such a pattern can be used to distinguish between a purely environmental failure in the hot section and one which has occurred primarily by erosion.

Mixed Mechanisms

In examining many catastrophic failures, the investigator often finds evidence of several failure mechanisms in addition to that which apparently led to the final failure. It is necessary in these instances to determine whether any of these other mechanisms might have contributed to, or actually caused, the final failure. Sometimes less damaging mechanisms, such as corrosion or wear, can lead to catastrophic failures, by changing the normal operating conditions or stresses in a component, and lead to the growth of a creep or fatigue crack. For example, base metal attack by corrosion or erosion can change the stress distribution in a component, particularly if the attack is localized and results in high stress concentrations. Likewise, wear failures can increase the amplitude of fatigue excitations by changing the damping of the component. The interplay between mechanisms will become more evident in the following examples.

CASE HISTORIES

The identification of the failure mechanism is just the first and, in many instances, the easiest step in the complete failure analysis. The more important role of failure analysis is to identify the conditions in the engine which have caused the failure to occur and then suggest solutions to correct the problem. These case histories are provided not only as examples of failures caused by the mechanisms discussed, but also to illustrate how, in most cases, it is necessary to go beyond a strictly metallurgical analysis to identify the cause of the failure.

Compressor Blade Failure

The following example is included to illustrate the importance of mechanical design analysis in determining the root cause of a failure.

A third stage compressor blade from a large industrial gas turbine had failed catastrophically after 15,000 hours of service. The fracture occurred approximately three-fourths of the way up the airfoil. A second blade was identified as having a large crack at approximately the same location in the middle of the airfoil.

Metallurgical examination of both the crack and the fracture revealed many of the features of a high cycle fatigue failure. The crack had propagated transgranularly, giving the fracture a smooth appearance. SEM examination revealed the presence of fatigue striations on the surface (Figures 17 and 18). A large number of beach marks were evident surrounding the apparent initiation of a small corrosion pit on the convex side of the airfoil. Similar pits were observed on the rest of the

airfoil, on both sides of the blade. However, the degree of pitting was no greater than that observed on many other compressor blades. It was concluded that some other factor had been responsible for the propagation of the fatigue crack.

Figure 17. Crack in a Compressor Turbine Blade Which Was Identified as Having Failed by High Cycle Fatigue. The surface has the typical smooth appearance of a fatigue crack.
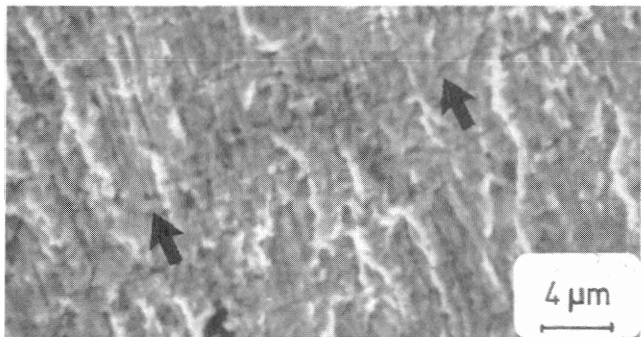

Figure 18. SEM Fractograph Showing Fatigue Striations Typical of a High Cycle Fatigue Mechanism.

A mechanical analysis was performed to determine whether some feature of the design may have predisposed the blade to fail in fatigue. It was discovered that the natural vibration frequency of the blade in the third transverse bending mode was potentially in resonance with the excitations caused by the inlet guide vanes and first and second rows of stator vanes at normal operating speeds (Figure 19). Cracks occurring by this mode would be expected to initiate at approximately 75 percent of the airfoil height, at the point of highest bending stress which, for this particular airfoil geometry, is on the convex side. This exactly corresponded to the observed initiation point of both the crack and the fracture of the failed blade. Thus, the major mechanical factor contributing to the failure was the resonance of the blades with the preceding stator stages.
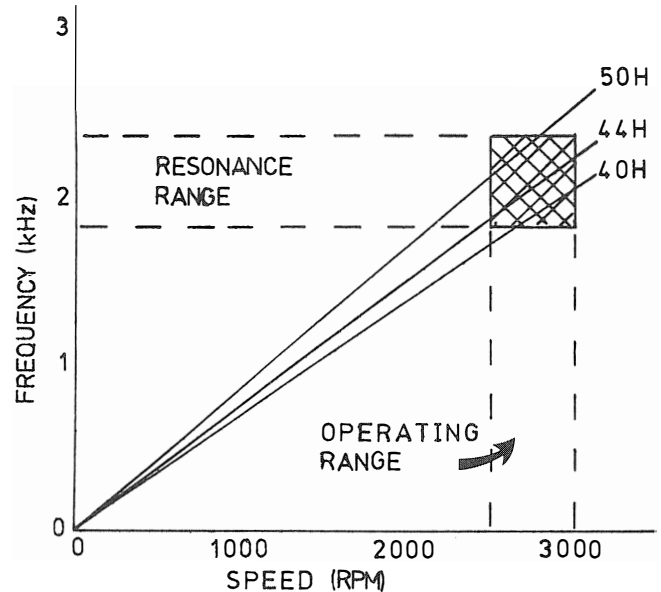

Figure 19. Campbell Diagram Showing Fatigue Excitation Resulting from Harmonics of the Running Speed. The excitation resulting from the inlet guide vanes and row 1 and row 2 stator vanes is resonant with the blades' natural vibration frequency in the third transverse bending mode.

The only feature of the failure left unexplained by the mechanical analysis was the relatively long life of the blade prior to failure. In general, failures occur very quickly if the components are resonant at operating speeds. Several factors appear to have combined to cause the failure to occur only after an extended period of time. First, the pitting would cause a stress concentrating effect which may have been required to initiate the crack. Since the growth of the pits is time dependent, some time would pass prior to the initiation of the fatigue crack. Secondly, the large number of beach marks evident on the fracture surface suggested that the resonant condition was not precisely at the running speed, but at the same speed at which the machine had run only intermittently, allowing many normal hours of operation to be accumulated without any growth of the crack. Finally, the engine inspection records revealed that some fouling of the inlet had occurred during service, which may have resulted in increased gas vibratory loading over time. However, the primary cause of the failure was the marginal design in which the blade was resonant at or near the operating speed. None of the contributing factors outline would have caused the failure in the absence of that resonant condition.

Mixed Mode Failure

In many cases, a complex chain of events leads to the final catastrophic failure of a critical component. Identifying the root cause of the failure in such a case requires reconstructing the sequence of events in a manner compatible with the available evidence. The following is an example of such a failure:

The gas turbine had been operating for approximately 10,000 hours since its last overhaul when it shut down, due to high vibration. A boroscope examination revealed damage to the combustion section and the first turbine stage. Debris from the combustion assembly was observed blocking the first stage nozzles in some areas. When the engine was disassembled, extensive cracking and fracture were evident on the combustors and their support assemblies (Figure 20). Severe fretting wear was also evident in the baffle strip support channels which retain the combustors (Figure 21). This was taken as evidence that the fit up of the baffle strips had been poor, allowing excessive rubbing in what was supposed to be a tight fit. In addition to the combustor damage, one first stage blade was found to have failed in the root section along with the adjacent disc fir tree (Figure 22).
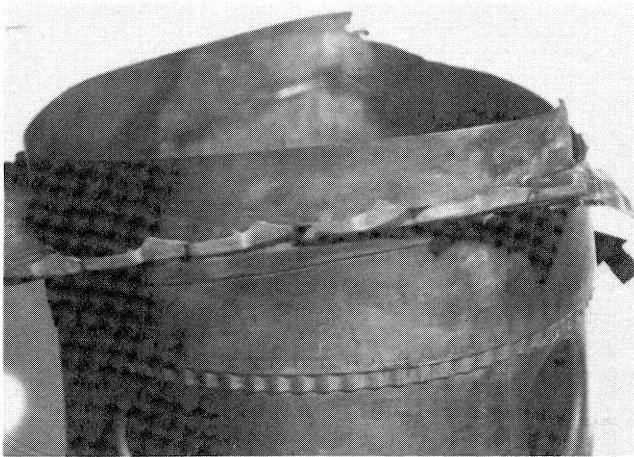

Figure 20. Failure of a Turbine Combustion System. Cracks have grown through the supporting flange baffle strip, the welded joint between combustors (arrow), and the combustor itself.
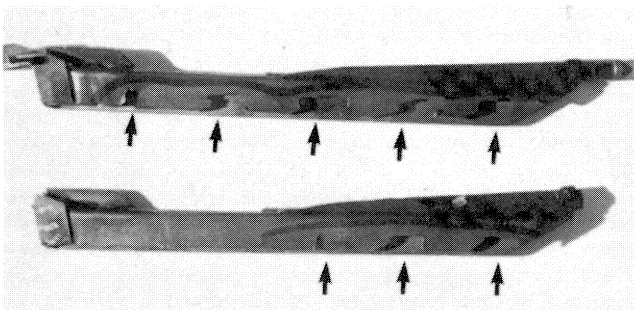

Figure 21. Heavy Fretting Wear of the Support Channels for the Combustor Shown in Figure 20. The channels have worn completely through in some areas (arrows).

Metallurgical analysis of the fractured disc fir tree and the combustion cracks revealed that both had apparently occurred by fatigue mechanisms. The combustion failures appeared to have initiated at the welds joining the individual combustion tubes. It was noted that some of the welds had been improperly located and were, in fact, missing in one location. The presence of extensive oxidation and smearing due to rubbing of
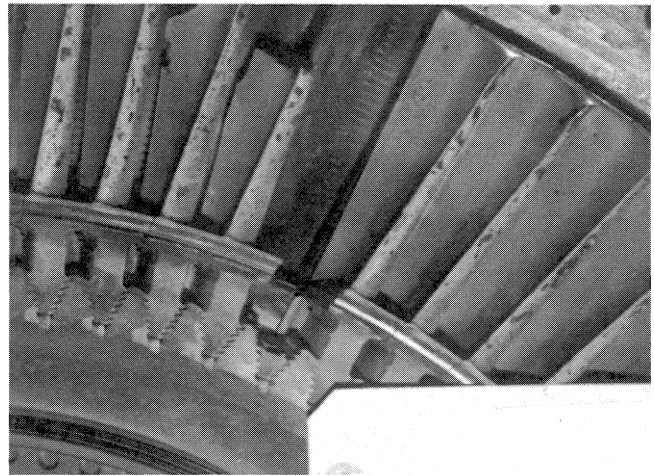

Figure 22. Failure of a First Stage Blade and Disc Fir Tree Associated with the Combustor Failure Shown in Figures 20 and 21.

the mating surface indicated that the cracks in the combustion system had occurred over a long period of time. By contrast, the fatigue crack in the disc had relatively few beach marks, suggesting that it had grown continuously and, therefore, rapidly. The fracture of the blade root appeared to have occurred by an overload mechanism.

Based on this evidence, the following failure sequence was identified. The combustion system appears to have failed first. Cracks initiated at the improperly welded joints between combustion tubes, due to the excessive vibration, allowed by the poor fit up of the baffle strip support system and the lack of damping. As the cracks grew in length, the combustion system was free to vibrate more extensively, thus accelerating the crack growth rate. Eventually, pieces of sheet metal came loose and became lodged in the first stage vanes, resulting in a very strong, once per revolution, impulse on the first stage blades. This excitation was transmitted to the disc, allowing the formation of the observed fatigue crack and impact failure of the blade, by debris from the combustor.

The recommendations made in this instance were based on the observation that the combustor damage which led to the failure initiated in the assembly of the combustor. Modifications to the assembly that were suggested to improve its reliability and inspection were performed at the rebuild of the engine to ensure that the welds had been properly located and the fit up in the baffle strips was satisfactory.

Disc Creep Failures

The goal of failure analysis is not only to determine the ultimate cause of the failure, but also to identify solutions to the problem to prevent its recurrence. In the following example, a chronic problem was solved by modifications to the turbine design.

In this case, a chronic disc cracking problem was being experienced in several units. The cracks generally occurred at the bottom serration of the disc fir trees and propagated across the load bearing section (Figure 23). Although in most cases the cracks were detected during periodic inspection, in at least one instance a catastrophic wreck had occurred.

Metallurgical analysis revealed that in all cases the cracks had propagated along the grain boundaries (Figure 24). In some instances, cavities were found to be present at the tip of the crack, providing convincing evidence that the cracks were occurring by a creep mechanism (Figure 25). A large degree of
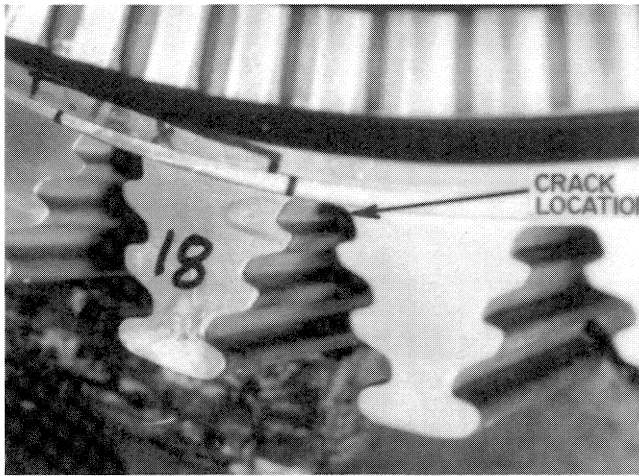
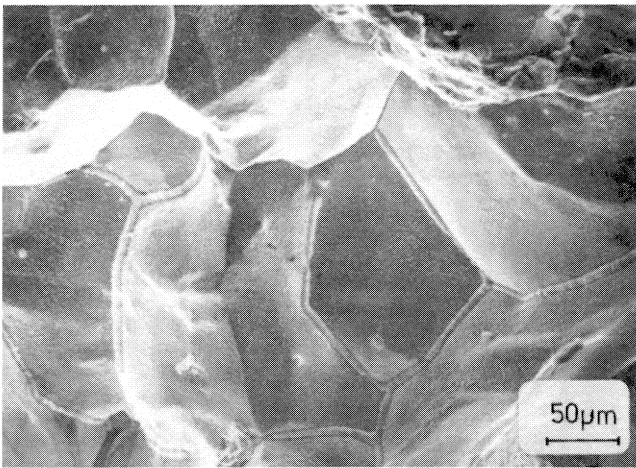Figure 23. Location of Chronic Cracks Found in Turbine Discs.

Figure 24. SEM Fractograph Indicating the Intergranular Nature of the Cracks Examined from the Disc Shown in Figure 22.
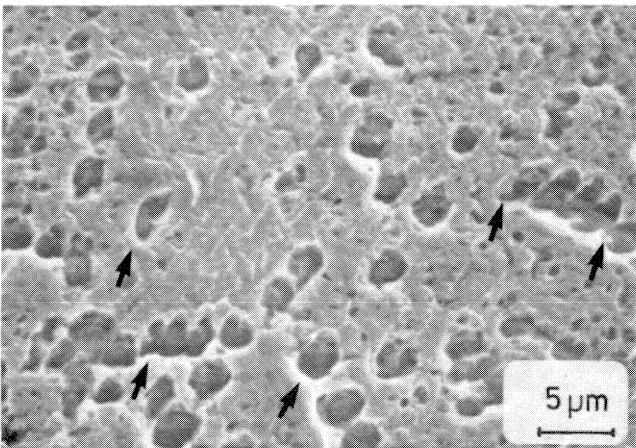

Figure 25. SEM Fractograph of Voids Found at the Edge of the Crack Shown in Figures 23 and 24. The intergranular nature of the crack and the presence of voids indicated that the crack was growing by a creep mechanism.

oxidation was observed in the cracks, indicating that high disc temperatures were providing the driving force for the

creep failures. This hypothesis was finally confirmed in an instrumented engine test which revealed abnormally high temperatures in the disc cavities.

In order to provide an explanation for the high disc and cavity temperatures, an engineering study of the gas path and cooling networks was performed by computer modelling. It was discovered that excessive ingestion of hot gas into the disc cavities was occurring, resulting in the observed temperatures. The proposed solution to the problem was to provide supplemental cooling air in such a way as to minimize hot gas ingestion and thus lower the disc temperatures. These changes were implemented and resulted in a 100°F to 300°F decrease in the disc cavity temperature, which coresponds to a 20 to 300 times increase in the creep life for the disc (Figure 26). The details of the engineering analysis, the design modification and the implementation of the changes are available for further study [1].
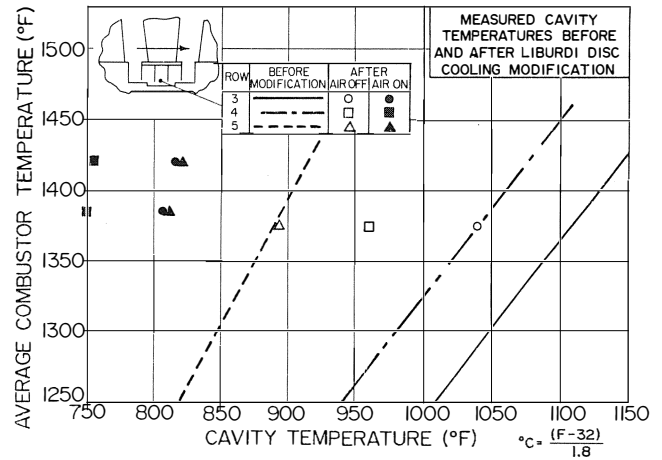

Figure 26. Decrease in Disc Temperature Cooling Modifications Implemented.

Figure Stage Blade Failure

Engine operating records can often provide important clues for identifying the cause of failure in cases where no apparent design or material deficiencies exist, as illustrated by the following case.

A catastrophic failure occurred in the first stage of an industrial turbine 1750 hours after the last overhaul. One blade was found to have failed in the third serration of the root and the two adjacent disc fir trees had large cracks running through them at the same location. Fluorescent penetrant inspection of the remainder of the blades and disc fir tree revealed the presence of a number of similar cracks in both the blades and the disc.

The examination of the cracks and fracture surfaces by metallography and SEM revealed the typical features of fatigue. The cracks were propagating in a transgranular fashion and fatigue striations and beach marks were evident on both blade and disc fractures (Figures 27 and 28). It was concluded that both the blades and the disc had formed fatigue cracks due to fatigue loading acting at the root of the blades. However, no apparent cause for the cracking could be identified in the mechanical design or materials.

Consultation with the engine operator identified several factors which, taken together, could have caused the cracks to initiate and grow. The engine records showed that, prior to the failure, the machine had been operating near the critical speed range with a high combustor temperature spread, which would result in high fatigue loading on the blades. It was also discovered that the disc had been in service for 40,000 hours and

Figure 27. Cracks on Two Disc Fir Trees Adjacent to a Blade which Failed Catastrophically in the Root. Beach marks are evident and the cracks appear to have initiated at the arrows.
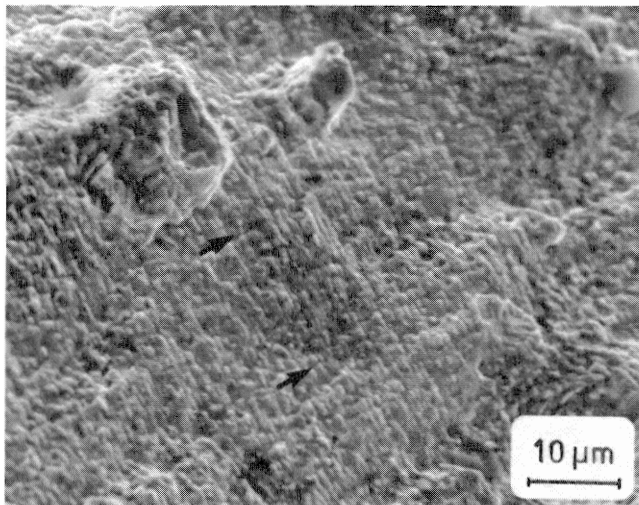

Figure 28. SEM Fractograph of Fatigue Striations Found on the Surface of the Blade which Failed Between the Two Disc Fir Trees Shown in Figure 27.

had been subjected to overspeed conditions for extended periods. The higher temperatures and stresses due to overspeed operation likely caused some creep, resulting in growth of the disc diameter. This would, in turn, loosen the fit between the disc fir trees and blade roots, resulting in a decrease in the fatigue damping efficiency.

It was recommended that the operator avoid operating the units with high combustion temperature spread, especially near the critical speed range, and that dimensional checks of long life discs be carried out at overhauls.

Gas Expander Disc Cracking

The following example shows the importance of ensuring that the proposed failure mechanisms developed from a metallurgical analysis are plausible, given the operating conditions of the engine.

An axial gas expander had been experiencing chronic disc failures for a number of years. Initially, two discs failed catastrophically and were analyzed as having cracked by an intergranular mechanism identified as caustic stress corrosion cracking. Recommendations made to address the stress corrosion

aspect were not successful and repeated cracking was experienced over a ten year period.

A re-examination of the failures led to different conclusions on the cause of the cracking. The fracture paths in the cracks examined were in fact intergranular, but a heavy oxide layer was also observed to be present on the crack surface (Figure 29), indicative of high temperature. Stress corrosion cracking was eliminated as a possible cause, since the operating temperature of the disc was expected to be well above the range for the proposed aqueous stress corrosion mechanism. Metallographic examination of the material also revealed extensive carbide precipitation, suggesting that it may have aged due to high temperature exposure during service.
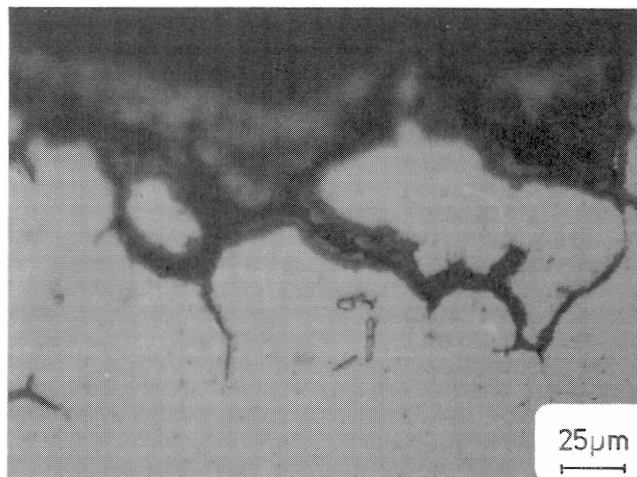

Figure 29. Photomicrograph Showing the Heavy Oxide Layer on the Fracture Surface of the Cracked Gas Expander Disc.

It was hypothesized that the cracks had grown by a creep or thermal fatigue mechanism, due to high operating temperatures. This was confirmed by stress rupture tests performed on the service exposed material, which revealed that the disc creep life was approximately 20 percent of that expected for new material, suggesting that service aging had indeed occurred.

The conclusion reached was that the material used in the discs did not have an adequate operating margin at the temperatures at which it was being used and, therefore, was prone to creep deformation. Accordingly, it was recommended that operating conditions be moderated as much as possible, to reduce the gas inlet temperatures and thermal cycling.

CONCLUSIONS

As illustrated by the examples, it is possible to learn from the expensive lessons provided by failures. Failures can be used constructively to correct any shortcoming in the design, inspection, metallurgy or operation of turbomachinery. The key to success in preventing the recurrence of expensive problems is the correct analysis, by experienced engineers, of the causes and contributing factors, and the implementation of recommended solutions and design modifications.

Failures must not be treated as solely a metallurgical phenomenon which often stops at the identification of the mode of cracking, but as a shared responsibility with design engineer and operations personnel.

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