INVESTIGATION OF FAILURE IN GAS TURBINES:
PART 2 — ENGINEERING AND METALLOGRAPHIC ASPECTS OF FAILURE INVESTIGATION

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ABSTRACT

This paper opens with a discussion of the various mechanisms of cracking and fracture encountered in gas turbine failures, and discusses the use of metallographic examination of crack and fracture surfaces. The various types of materials used in the major components of heavy-duty industrial and aeroderivative gas turbines are tabulated. A collection of macroscopic and microscopic fractographs of the various mechanisms of failure in gas turbine components is then presented for reference in failure investigation. A discussion of compressor damage due to surge, as well as some overall observations on component failures, follows. Finally, a listing of the most likely types of failure of the various major components is given.

INTRODUCTION

This paper is the second part of a two-part series on investigation of failures in gas turbines. The first part outlined the principles of successful failure investigation, and described the personal qualities and habits of mind necessary for failure investigators. Examples of investigations illustrating the principles outlined were given. This second part presents particulars of the mechanisms characteristic of failures of gas turbine components, including the metallographical features of the fracture surfaces, and the meaning of rub patterns that may be found. The intent is to present an atlas of information for direct use in investigation of such failures.

MATERIALS USED IN MAJOR GAS TURBINE COMPONENTS

Table 1 is a list of typical materials used in the major components of heavy-duty industrial and aeroderivative gas turbines. The exact alloy composition is not of importance in failure investigation, although extensive efforts are often made to determine it, as well as to determine the mechanical properties. It can practically always be taken for granted that the manufacturer specified a material suitable for the service, and that the material met the manufacturer's specifications for mechanical and physical properties. It can be assumed that the material used in rotating components is ductile and that the features of a fracture surface are characteristic of ductile materials. Even the nickel-base superalloys used in turbine blades, which have low elongation and ductility at room temperature, have satisfactory elongation at their operating temperatures. There is one exception to the above precept: some alloys have been found to become embrittled after a period of operation at elevated temperature. This problem is dealt with later in the paper.

MECHANISMS OF CRACKING AND FRACTURE

Cracks and fractures in gas turbine parts, both rotating and stationary, occur as a result of four mechanisms: short-term loading, fatigue, creep, and embrittlement. In practically all cases of short-term loading, cracks progress almost instantly to complete fracture. Fatigue, creep, and embrittlement are time-dependent phenomena, so cracks may sometimes be manifest before complete fracture occurs. Further, there are several significant variations of fatigue; these are: high-cycle fatigue, high-frequency fatigue, low-cycle fatigue, and thermal fatigue. Another variation of fatigue -- corrosion fatigue -- is of interest in failure analysis of steam turbines, but has not been a major hazard in gas turbines. It is necessary to recognize the possibility of this mechanism, however.

It is necessary in metallographic examinations to distinguish between ductile and brittle materials. However, almost all materials of importance in gas turbine failure investigations are ductile. Exceptions would be cast materials used for stationary frames; these, for all practical purposes, never experience major failures. Nickel-base alloys used in turbine blades have very low ductility at room temperature, but they are quite ductile at their operating temperatures.

Presented at the International Gas Turbine and Aeroengine Congress and Exposition
Cincinnati, Ohio — May 24-27, 1993
Table 1. Typical Gas Turbine Materials

<table>
<thead>
<tr>
<th>Components</th>
<th>Heavy-Duty Gas Turbines</th>
<th>Aeroderivative Gas Turbines</th>
</tr>
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<tbody>
<tr>
<td>Compressors Disks</td>
<td>Low-alloy steel e.g., Cr-Mo-V</td>
<td>A286 high-nickel steel 6A1-4V titanium alloy Inco 718 nickel-base alloy</td>
</tr>
<tr>
<td>Blades</td>
<td>12Cr stainless steel</td>
<td>A286 high-nickel steel 6A1-4V titanium alloy</td>
</tr>
<tr>
<td>Stator Vanes</td>
<td>12Cr stainless steel</td>
<td>A286 high-nickel steel 6A1-4V titanium alloy</td>
</tr>
<tr>
<td>Casings</td>
<td>Grey cast iron</td>
<td>Precipitation-hardening stainless steel (17-4PH) Inco 718 nickel-base alloy</td>
</tr>
<tr>
<td>Combustors Liner</td>
<td>Hastelloy X (nickel-base)</td>
<td>Hastelloy X (nickel-base)</td>
</tr>
<tr>
<td>Casings</td>
<td>Ductile cast iron</td>
<td>Inco 718 nickel-base alloy</td>
</tr>
<tr>
<td>Turbines Disks</td>
<td>Low-alloy steel e.g., Cr-Mo-V</td>
<td>Inco 718 nickel-base alloy</td>
</tr>
<tr>
<td>Blades</td>
<td>Investment-cast IN-738 nickel-base superalloy</td>
<td>Investment-cast Rene 80 nickel-base superalloy</td>
</tr>
<tr>
<td>Nozzle Vanes</td>
<td>Investment-cast cobalt-base superalloy e.g., X-40</td>
<td>Investment-cast cobalt-base superalloy e.g., X-40</td>
</tr>
<tr>
<td>Casings</td>
<td>Fabricated carbon steel e.g., SA516</td>
<td>Inco 718 nickel-base alloy</td>
</tr>
</tbody>
</table>

The features of cracks and of fracture surfaces provide indications as to which of the above mechanisms produced the crack or fracture. These can be studied by the disciplines of fractography and metallography. The list of references at the end of this chapter contains the titles of some treatises on these disciplines.

The examination of fracture surfaces (fractography) may be done macroscopically or microscopically. Macroscopic examination is usually considered to be that done with the naked eye, or with no more than a magnification of ten. There are two ranges of microscopic examination of significance in fractography: the first is by means of optical microscopy, and usually extends up to 60-power, while the second must be performed with scanning electron microscopy. Using this technique magnifications of 5,000 (or greater, if necessary) can be obtained.

Instantaneous Mechanisms of Cracking and Fracture

Short-Time Fracture. Short-time fracture occurs when a component is overloaded, as in a tensile-testing machine. The only way this can occur in a gas turbine is through rotor overspeed, and a rotating disk is always the part with the least margin on speed. It is usually clear when a gas turbine has oversped, so metallographic analysis is usually unnecessary. Nevertheless, a knowledge of the features of the resulting fracture surfaces is valuable, if only to provide a contrast with other types of fracture for diagnostic purposes.

Ductile material fractures as a result of shearing flow of the material at an angle approximately 45 to the applied stress. This gives rise to a characteristic appearance of the fracture surface, typified often by a lip at the edge, formed by shearing forces as the two parts of the component separate (Figure 1). The face of the fracture surface tends to be rough and angular because of the shearing flow.

Ductile fractures are usually transgranular, while brittle fractures are usually intergranular. Microscopic examination of the short-time fracture surface in a ductile material reveals a phenomenon known as dimples (Figure 2). These are formed by plastic stretching of the crystals as the specimen deforms. Dimples normal to the direction of loading are roughly equiaxed, as in the figure; if there is a transverse component of loading, the dimples may be slightly elongated. Magnifications of 3000 are usually required for the identification of dimples.

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Figures 3a,b and c show additional short-time fractures of materials typically used in gas turbine components. The tests were all taken in unnotched round specimens, and show large shear lips (cones) around the edges.

Impact Fracture. When a rotating blade in a gas turbine fractures, it becomes a high-energy missile and can do extensive impact damage to other blades in the same and following rows. Many additional blades may be fractured by impact. It is, therefore, necessary when investigating a gas turbine failure involving the fractures of many rotating blades, to determine which blade failed first; sometimes this is obvious (as in the case of high-cycle fatigue, as will be seen), but it is usually less obvious (as in the case of creep rupture). It helps, therefore, to recognize the characteristics of a short-term impact fracture.

Impact fracture of a rotating blade involves a combination of bending and transverse shear. In the bending mode, the fibers on the side of impact are in tension, and the tension field quickly moves across the blade as the fracture progresses to completion. The macroscopic fracture surface is rough and angular like those illustrated in Figure 3; however, there may be a distinct pattern of ridges roughly parallel to the direction of fracture progression. Figure 4 shows the fracture surface of a notched bar of 12-chrome stainless steel. This bar was broken by two hammer blows. After the first, the crack originated at O and progressed along the curved lines C to arrest lines A and B; after the second blow, the fracture progressed to completion along the ridges D. In this case, the ridges converge toward the origin of the fracture, i.e., the point of impact.

Figure 5 is also illustrative of the features of impact fracture involving a thin section. The characteristics of such a fracture would be typical of the impact fracture of a thin compressor blade, or of a thin-walled turbine nozzle vane or blade.

Fatigue Failures

Prevention of fatigue failures is one of the most important aspects of the design, operation, and tenance of turbomachinery. The mechanisms of fatigue and the recognition of fatigue failure are, therefore, among the most important aspects of investigation of failures in such machines. The subject is extensive, and cannot be dealt with here other than to present guidelines that will be useful.
in almost all cases. Exceptions usually involve distinguishing between high-cycle and low-cycle fatigue and recognizing true fatigue striations. ASM (1974 and 1987) discuss these topics in detail. These references, however, use different definitions of high-cycle and low-cycle fatigue (based on the nature of the crack progression) than are used here. Those used here are based on the functional mechanisms -- cycles of operation or high-frequency vibration -- that lead to the fatigue. This distinction is of more value in the present context.

Fatigue failures in turbomachinery may be described as either not life-related or life-related. The first category consists of high-frequency fatigue due to blade, stationary vane, and disk vibration. This is usually resonant vibration, but, increasingly, there are examples of self-excited vibration or flutter.

The second category consists of low-cycle fatigue, thermal fatigue, and corrosion fatigue. High-cycle fatigue of shafts, arising from the alternating stress caused by a steady transverse load, may be of either category: it may be due to bearing misalignment -- not life-related -- or, in some rare instances in steam turbines, it may be due to the self-weight of the rotor. The first type can be prevented by attention to bearing alignment. The second category should be considered life-related, since fatigue cracking will eventually occur if the machine continues to run, subject only to the variables of material fatigue strength and the severity of the local stress raising mechanism.

The stress/cycles curve of Figure 6 shows in very general terms the cycle regimes of the various types of fatigue. At the left, up to 10,000 cycles is the regime of low-cycle fatigue and thermal fatigue. These cycles involve cycles of operation -- startups, followed by periods of operation and shutdown. The upper end of this range may never be realized, although aircraft engines are designed for up to 20,000 cycles. At the other end, a case is known of a low-cycle fatigue failure of a turbine disk in an industrial gas turbine in 530 cycles.

At the right of Figure 6 is the high-cycle or high-frequency fatigue regime. The S-N curve is essentially a horizontal line known as the fatigue strength or endurance limit. For most materials used in gas turbines the S-N curve "runs out," that is, if a component subject to alternating stress achieves 10^7 cycles of stress, the fatigue life should be indefinite.

The curve in Figure 6 represents the number of cycles at which the first discernible (by usual nondestructive testing) fatigue crack appears on the surface. This is generally considered to be a crack 0.03-0.06 in. (0.76-1.52 mm) long. The damaging effect of the alternating stress is in elastic straining of the material at the point of maximum stress. Each cycle imposes nonrecoverable strain on the material, and eventually this plastic strain develops into a discreet crack normal to the direction of stressing. After this crack develops, continued stressing causes it to grow at an accelerated rate and progress over a large percentage of the cross-section until the remaining cross-section is too small to withstand any steady applied load, and the part fractures instantaneously in a ductile manner as illustrated in Figure 1.

A material flaw that can be reliably detected by nondestructive testing is no larger than the smallest detectable crack. This means that a new part that has passed inspection for flaws actually contain minute flaws or inclusions up to 0.03-0.06 in. (0.76-1.52 mm) in size. If the part is then subjected to vibratory or other alternating stress to failure, the crack will be initiated at some one of these minute flaws. The cause of the failure is often incorrectly attributed to the flaw, when the real cause is the condition that resulted in the alternating stress or vibration (in the case of high-cycle fatigue), or the number of cycles that part has experienced (in the case of low-cycle fatigue).

High-Cycle Fatigue. The high-cycle regime is usually considered to start at 10^6 cycles, and involves stresses that are usually just above the fatigue strength after stress concentrations are included, unless the component suffers damage that would increase the stress concentration at the point of maximum stress, or the material becomes corroded. The latter circumstance is the basis of corrosion fatigue. The concentrated alternating stress may not exceed the fatigue strength in the new component, but after a period of pitting or developing surface roughness from corrosion, the fatigue strength is progressively reduced until it is inadequate to withstand the applied stress and a fatigue crack is initiated.

High-frequency fatigue falls into the category of high-cycle fatigue. However, the process of failure in high-frequency fatigue is brief: once the excessive alternating vibratory stresses are established, the initial crack appears in 14 hours at a vibratory frequency of 200 Hz -- a typically low value. Final fracture occurs in no more than a few hours after that. This explains the earlier statement that high-frequency fatigue is not life-related.

If the misalignment of the bearings of a gas turbine is sufficient to produce alternating stresses in the shaft above the fatigue strength, the shaft will eventually fail in high-cycle fatigue. Cycles of alternating stress build up at the rate of one per revolution; 10^7 cycles could be developed in approximately 50 hrs at that rate, and, after initiation of a fatigue crack, final fracture would occur in relatively few hours. Crack progression in a rotating shaft may be complex, however, and experience suggests that bearing vibration resulting from a cracked shaft may persist for several days before complete fracture occurs. It is clear, however, that high-cycle fatigue due to bearing misalignment is not a life-related failure mode.
Figure 7. High-cycle fatigue fractures of turbo machinery blades, showing typical beachmarks. (a) Compressor blade of precipitation-hardening stainless steel, (b) Compressor blade of A286 high-nickel stainless steel.

Figure 7 shows the surfaces of turbomachinery blades of two different materials that had fractured in high-frequency fatigue. In each instance the crack progressed in an elliptical pattern from an origin on the blade surface until it covered 40% or more of the blade cross section. The crack surface is smooth, while the short-term final fracture surface is rough and characteristic of a ductile material (Figure 1). The crack surface contains distinctive lines or patterns concentric with the origin. These lines or patterns are known as beachmarks. They are associated with progression of the crack at different rates and stress levels as it extends through the blade cross section. In the cases illustrated, the beachmarks are easily identified. In some cases they are not definitively evident, although there may be a hint of fatigue progression in the shape of the crack. In all investigations of turbomachinery blade failure, microscopic examination should be undertaken whenever the crack surface is smooth and does not extend over the entire cross section, even if beachmarks are not clearly evident.

Scanning or transmission electron microscopy (SEM or TEM) can be used for microscopic examination of a cracked surface. The former is used where a small sample of the crack surface can be cut away from the failed part, while the latter involves replication of the crack surface and microscopic examination of the replica. Magnifications of up to 10,000X can be obtained with either of these techniques.

Microscopic examination of a surface cracked by fatigue almost always reveals the phenomenon of fatigue striations. These are closely spaced parallel lines indicating the cyclic progression of a high-cycle fatigue crack in a direction normal to them. Figure 8 shows striations in two materials of the type used in gas turbines. Figure 8a is an excellent view of high-cycle fatigue striations even though the magnification (2650X) is relatively low. In Figure 8b, the striations are more difficult to detect, although they are clearly present. The magnification in this case is 4000X. It is probable that the striations would not be visible at the magnification used in Figure 8a, and that they would be more evident at a magnification, say, of 5000X. Magnifications of this order or larger should be used in the examination of cracked surfaces if high-cycle fatigue is suspected. If striations are not visible at lower magnifications, say, of 2000X, it should not be assumed that they are absent. On the other hand, it cannot be assumed that a failure is due to high-cycle fatigue until the fracture surface has been examined under sufficient magnification to identify striations clearly.

Care must be exercised in the identification of high-cycle fatigue striations. There are a number of microscopic features with which they can be confused. One of the most important is Wallner lines (Figure 9). This structure is characteristic of the fracture of brittle phases in otherwise ductile materials. Fatigue striations differ in that they never cross each other, as can be seen clearly in Figure 8a, and somewhat less clearly in Figure 8b. That, in general, is their defining characteristic.

Low-Cycle Fatigue. Low-cycle fatigue is a characteristic failure mode of components in which normal operating centrifugal stresses are close to the yield strength of the material, and which may be higher than...
Low-cycle fatigue failure due to centrifugal stresses alone is rare in industrial gas turbines. However, thermal fatigue, in which the centrifugal stresses are accompanied by thermal strains due to thermal gradients from bore to rim of the disk during startups and shutdowns, is a significant hazard to turbine disks. It occurs when the total strain (centrifugal and thermal) includes substantial plastic component, and involves cycles of straining over the complete operating range of the machine. Figure 10 illustrates the mechanism of straining of a turbine disk during a cycle of operation. Figure 10a shows how the rim of the disk heats up faster than the bore during startup, and Figure 10b shows that this produces a high compressive (overpowering the tensile centrifugal stress) stress at the rim at some point in the startup procedure. Exactly the opposite occurs during shutdown. As shown in Figure 10b, a point in the disk (e.g., at the rim) experience a large total strain excursion. If there is a minute flaw at this point, each cycle of operation will cause the flaw to grow until it has reached the critical size, and the disk ruptures rapidly under additional cycles of operation, as described earlier.

A purer form of thermal fatigue occurs in turbine stationary nozzle vanes. These, especially in the first stage, are exposed to the hottest temperatures in the gas turbine at maximum power. They are cooled, but it is largely to extend the thermal fatigue life of the nozzle vanes as far as possible or economical. The mechanical stresses involved are low, and the crack development is almost entirely due to the thermal gradients developed throughout the parts because of the constraints the various sections of the vane structure impose on each other. Thermal cracks often develop after relatively few cycles of operation; however, once a crack starts, it tends to relieve the thermal strains that produced it, and its growth is slowed rather than accelerated during subsequent cycles. A certain amount of cracking, therefore, can be tolerated, subject to cyclic limits developed by experience, and as long as the cooling flow in the nozzle vane is not disrupted. Continued cycling can lead to cascading breakup of the nozzle vanes with extensive downstream damage. If a fuel nozzle deteriorates, as by being blocked, or if the combustor suffers serious damage, severe hot spots (more severe than those anticipated in design) can develop in the flowpath at the nozzles; continued cycling will cause breakup of the nozzles.

Combustor cracking is often caused by this form of thermal fatigue also. Thermal cracks develop after a relatively small number of cycles of operation with severe hot spots because of nonuniform combustion; the combustor cooling flow is badly disrupted as the cracks open up, and the cracks progress to complete disintegration of the combustor.

The crack surfaces of parts that have failed in low-cycle or thermal fatigue are not easily distinguishable from those that have failed in high-cycle fatigue. Since disks can, and do, fail in high-frequency fatigue also, detailed microscopic examination of the fracture surface should be undertaken whenever fatigue is suspected.

Figure 11 shows low-cycle fatigue striations in three typical materials. Low-cycle fatigue striations tend to be broader than high-cycle fatigue striations. They also tend to be discontinuous, and to terminate in the distinctive lap evident in Figures 11a, b, and c. Sometimes the striation spacing can be seen to

![Figure 9. Wallner's lines, sometimes mistaken for fatigue striations (6400 X). (Colangelo and Heiser, 1974, p. 105).](image)

![Figure 10. Cyclic thermal gradients and strains at rim and bore of a gas turbine disk during startup and shutdown. (a) Thermal gradients. (b) Thermal strains.](image)
increase as the crack progresses to the critical value. This is due to the increasing stress on the net cross section as it decreases due to the progression.

Long-Time Rupture

A component subject to stress and high temperature over a period of time is subject to the phenomenon of creep, as illustrated in Figure 12. The creep curve shown is at constant stress and temperature; it is characterized for engineering purposes by two quantities -- the creep rate, and the time to rupture. Creep rate is the total strain divided by the time; it ignores the instantaneous and primary creep strains as being insignificant where long times are involved. Failure is taken as the initiation of tertiary creep, after which the component stretches unstably to the point of fracture.

The gas turbine components most likely to experience stress-rupture are the turbine blades, although Dundas (1993) gives an example of creep growth and cracking of a turbine disk. Blades may be designed for creep lives of up to 60,000 hours, but extrapolation of laboratory creep data to such long hold times is uncertain, and premature failures have taken place. If the blade cooling air is interrupted, failure may take place in a very short time.

For a part subjected to a constant stress at an elevated temperature over a long time, time-to-rupture and temperature are thought of as interchangeable. Figure 13 shows the relationship between these quantities for In 738, a typical turbine blade material, subjected to a typical average centrifugal stress of 35,000 psi (240 MPa). The life is seen to be very sensitive to temperature: for a life of 50,000 hrs, the temperature must be no higher than 1415 °F (770°C); if the temperature is increased by 25 °F (14 °C), the life drops to 23,000 hrs -- a factor of 2.2. If blade cooling is lost, the temperature may increase by 300°F (170°C), and the life would then drop to 17 hrs. Dundas (1993) gives an example of such an event.

As a ductile material undergoes creep under stress at elevated temperature, voids develop in the grain boundaries as the grains move relative to one another. This intergranular separation is the basis for the
replication method of inspection of piping for creep damage (Neubauer and Wedel, 1984). Thus, stress rupture fractures in ductile materials are intergranular, and are characterized by the above-mentioned voids. They have similar macrographic characteristics to short-term fractures (Figures 1 and 3), but they tend to have a more uneven fracture surface because of the greater plastic flow experienced as a result of creep. Figure 14 is fractograph of the nickel-base alloy Waspaloy, often used in turbine blades, at a moderate SEM magnification.

**Embrittlement**

In-service embrittlement of rotating components exposed to elevated temperatures is a distinct hazard in steam and gas turbines. Impurity-induced embrittlement, leading to catastrophic rupture, in steam turbine rotors has been of concern since the 50's. Recently embrittlement of gas turbine disks of Inco 718 has become of concern also. This phenomenon has been termed time-dependent notch sensitivity (Feldstein and Mendoza, 1989). The mechanism consists of the transformation of gamma double prime plates into round gamma prime and delta plates in the grain boundaries under the influence of temperature and long service times (Feldstein and Mendoza, 1989 and Radavich, 1989). When this transformation occurs, the notch-sensitivity of the alloy is significantly reduced, and brittle cracks and fractures can occur in areas of high stress concentration, as in notches. Figure 15a,b shows the development of these platelets of delta phase over a period of time at a temperature of about 1300 F (705 C).

These platelets, of delta phase, which appear as stringers in transverse view, are characteristic of fractures due to time-dependent notch sensitivity.

**DAMAGE DUE TO SURGE**

When the compressor of a gas turbine surges, large dynamic loads are generated on the pressure sides of the blading. The blades deflect forward, generally in groups. Two types of damage may result from a severe surge, as illustrated in Figure 16. Clashing occurs when the blade deflection is great enough to impact

![Figure 16](image1.png)

**Figure 16.** The mechanisms of compressor blade damage during surge.
the trailing edges of a previous row of stator vanes. The blades leave a triangular impact footprint in the trailing edges of the vanes near the outer flowpath wall. Figure 17a shows clashmarks on a compressor stator vane as a result of a devastating surge incident. The vanes are sometimes torn or broken off completely by the impact.

Figure 17b shows typical damage to the rotating blades due to severe surge. The leading edges at the tips are bent back (opposite to the direction of rotation) as a result of clashing with the stators. The blades may be torn or completely fractured.

When surge occurs during normal operation, the damage tends to occur midway along the compressor; if surge occurs during startup, the damage tends to be in the early stages. This is not a generalization, however, since much depends on the design of the compressor, as well as on the time surge occurs in the startup cycle. The second type of surge-related damage is clanging. This occurs when groups of blades deflect in a wave pattern; the blades do not all deflect the same amount, and the tip trailing edges impact the leading edges of the adjacent blades on the pressure sides (Figure 16b). Clanging does not tend to be catastrophic, since complete blades are usually not broken off. The tip corners of the blades do, however, suffer significant damage in the form of bending, tearing, and even local fractures. Figure 18 shows compressor damage that has been attributed to clanging.

Surge damage includes a great deal of impact damage. For this reason it is often attributed to foreign object or loose part damage. However, the impacts during surge have a distinctive pattern that can usually be readily identified. Unless a foreign object or loose part can be readily identified, caution should be exercised in dismissing the possibility of surge, and the damage patterns described above should be identified, if possible.

The operating condition at which the failure occurred is of fundamental significance also. Surge is most likely to occur at low power settings and when the gas turbine output has deteriorated (Dundas, 1988). It also occurs during startup; these occurrences usually involve malfunction of the compressor bleed valve. Dundas (1992) recommends that the compressor map be monitored directly as part of performance monitoring, both to avoid operating conditions where surge may be a hazard and to assist in post-mortem diagnoses.

RUBBING PATTERNS

Many failures in gas turbines involve radial rubbing between rotating components and stationary blade rings or seal lands. An understanding of these patterns is often of major assistance in failure investigation. Figure 19 shows the most common combinations of rubs on the rotor and stator. They are:

A. 360 rub on both rotor and stator: The rotor and stator have bound radially at some time during operation, probably during startup or shutdown when this condition is more likely. There is insufficient radial clearance between rotor and stator.

B. 360 rub on rotor, local rub on stator: The stator is misaligned (offset) relative to the rotor bearings.

C. 360 rub on stator, local rub on the rotor: This is caused by excessive rotor whirl.
Table 2. Failure Mechanisms of Gas Turbine Components

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<tr>
<td>Compressors</td>
<td>Disks</td>
<td>High-cycle fatigue.</td>
</tr>
<tr>
<td>Bladed</td>
<td>Low-cycle fatigue.</td>
<td>Low-cycle fatigue.</td>
</tr>
<tr>
<td>Blades</td>
<td>High-frequency fatigue due to resonant vibration.</td>
<td>High-frequency fatigue due to resonant vibration.</td>
</tr>
<tr>
<td>Stator Vanes</td>
<td>Clashing and clanging due to vibration.</td>
<td>Clashing and clanging due to vibration.</td>
</tr>
<tr>
<td>Combustors</td>
<td>Liner</td>
<td>High-frequency fatigue due to flutter.</td>
</tr>
<tr>
<td>Turbines</td>
<td>Disks</td>
<td>High-frequency fatigue due to resonant vibration or flutter.</td>
</tr>
<tr>
<td>Bladed</td>
<td>Thermal fatigue.</td>
<td>Thermal fatigue.</td>
</tr>
<tr>
<td>Muzzle vanes</td>
<td>Creep-fatigue.</td>
<td>Thermal fatigue.</td>
</tr>
<tr>
<td>Nozzle vanes</td>
<td>Creep.</td>
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</tbody>
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Table of typical materials used in the major components of gas turbines and of the usual failure modes associated with each component are also presented.

ACKNOWLEDGEMENTS

The author wishes to express his gratitude and appreciation for the assistance provided by Mark Gilkey of the Factory Mutual Research Corporation Metallurgical Laboratory in reviewing the discussions of metallography and fractographs in this paper.

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REFERENCES


