

Repair assessment and modification of gas turbine components and assemblies

Lifetime extension

Gas turbine components have different life-limiting failure modes. Life-limiting deterioration is frequently created by a detail of a component. A thorough analysis and creative thinking can lead to modifications that result in substantial extensions of turbine lifetime.

Gas turbine components are subjected to high temperatures, as well as high stress levels, and are exposed to aggressive gases at the same time. Gas turbines have to be fired to highest possible temperatures to get the best efficiency and the highest output. Fighting degradation of components exposed to high temperature is a continuous challenge.

Factors affecting gas turbine component lifetime

The steady-state temperature is the first factor. It controls oxidation and corrosion rates, degradation of base material quality, and creep lifetime. Creep lifetime is very dependent on material temperature. Gas turbine hot-section [1] components are made of nickel-base and cobalt-base superalloys. Excessive temperature can affect the material integrally—sometimes irreversibly. Thermal cycling creates

cyclic stress loads, which can be very severe. Most cracking of gas turbine components is a consequence of thermal cycling [2]. Thermal cycling cracks can occur in sound material as well as in aged material [3].

Stresses are factor number two

Steady-state stress levels in materials that are subjected to high temperature will lead to creep, which is a slow continuous plastic deformation of the material. Cyclic stresses can lead to fatigue, which is the initiation and growth of cracks by cyclic stress. Cyclic temperature changes while starting and stopping can create very high cyclic stresses. As a result, cracks can initiate and grow during even a very low number of stress cycles.

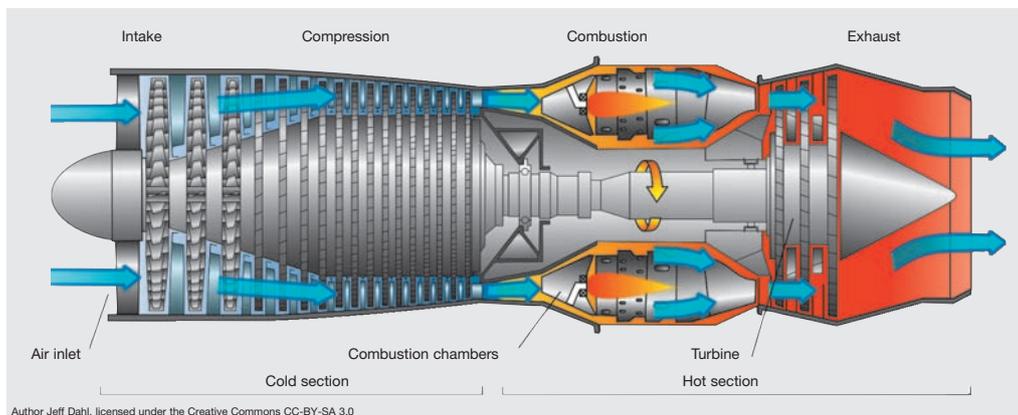
Fatigue by thermal cycling thus is known as “thermal fatigue” and “low-cycle fatigue.” When a component is weakened by internal degradation of the

base material, it becomes much more sensitive to thermal fatigue. Cyclic stresses can be created by external mechanical excitation, like tip rubbing or rattling of combustion components or by irregularities in the gas flow pattern that create cyclic pressure loads on components. Usually, the cyclic stress level is low and the vibration frequency is high.

It is worth mentioning that the crack growth rate under identical stress and temperature conditions is very similar for most superalloys. Stronger alloys show a longer crack initiation time, but, after initiation, the crack growth rate is nearly the same as for weaker alloys.

Many high-cycle fatigue failures are caused by components that have developed cracks by excitation of a harmonic mode. At the same time, it is very important to understand that pure cyclic mechanical overstressing (by forced vibration) can make a component fail just

[1] Functional design of a gas turbine.



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as easily. In all cases, it is important to determine and address the root cause of the mechanical excitation rather than just focus on the determination and trimming of natural frequencies. Initiation of cracks, growth, and ultimate failure usually take place in the range of thousands to some millions of cycles. Because of the high frequency, this can happen rather quickly.

The excitation of a natural frequency in gas turbine components can lead to severe amplification of the cyclic stress level and to failure in a very brief period of time (seconds to minutes). Especially long rotating blades can be sensitive to excitation.

Oxidation and corrosion are other factors

Superalloys are a blend of many elements, of which, many are very sensitive to oxidation. Like in stainless steel, the alloys are protected against oxidation and corrosion by the formation of a stable, dense, and tight oxide scale.

Depending on the alloy (or the coating), this scale can be either chromium oxide or aluminum oxide. Industrial gas turbines with very long operating times benefit from high-chromium alloys; turbines in which the alloys are exposed to the highest temperatures benefit from high aluminum contents. The latter turbines cannot offer the fuel flexibility for which old, “low”-temperature gas turbines were once known. Only chromium oxides can offer reasonable protection against attack by sodium sulphate or sodium vanadate salts (“hot corrosion”).

All modern gas turbines, as used in public utilities, operate with high metal temperatures. They are protected by high-aluminum coatings and need very clean fuel gas and combustion air. Up to about 750 °C, the combustion gases only attack the material at its surface or, to some extent, along grain boundaries.

At higher temperatures, diffusion in the alloy becomes increasingly important and, consequently, oxygen and other reactive components from the combustion gases



2 First-stage blade after coating removal and cleaning. It exhibits thermal cycling cracking in the leading edge and on the airfoil.

can penetrate deep into the surface of the component. In this surface layer, alloying elements react in order of decreasing reactivity, leading to depletion and formation of internal oxides, nitrides etc. Because of the high stability of these compounds, this cannot be restored [4].

Damage in gas turbine components

The damage created by the mechanisms above renders the information that is needed to assess the severity of the process creating it. If this damage had been foreseeable in its full extent in the design phase, appropriate design modifications would already have been implemented in that phase.

Therefore, pure reverse engineering, in which, essentially, the same calculations and estimations are made as in the original design phase, cannot be guaranteed to offer a good analysis and solution. It is a valuable instrument to support modification initiatives. If a solution to or a mitigation of a problem is possible, often a great deal of additional information can be retrieved from the used and damaged components, especially when there is an opportunity to compare these components with similar components from other turbines and other types and/or brands of turbines. From such experience data, the following comments on generic types of damage can be made.

Creep

Creep is slow plastic deformation that occurs in a component under stress at high metal temperature. The creep process gradually exhausts the plastic deformation capability of the component. Up to about two percent plastic deformation does not usually create serious problems with the alloy. In many cases, however, the accompanying mechanical deformation already exceeds acceptance limits for safe operation.

This creep damage can be repaired—not by addressing the material or the root cause of the problem—but by mechanical correction of dimensions, e.g., by cutting back and by rebuilding as required. Since the deformation of straightening actions adds up to the creep damage, the straightening process should not be used for critical components. It should be emphasized that in many cases of creep damage, the base material is still in very good shape, e.g., it would be pronounced “to be in good shape” by an investigating metallurgist.

This is not contradictory to a rejection of that same component because of mechanical non-conformance. Practical experience shows that true metallurgical creep damage is a rare phenomenon. Most gas turbine components exhibit a metallurgical creep life that is a multiple of the actual lifetime.

Material degradation

When components are produced, the materials structure have the right grain size distribution and size and distribution of different phases like carbides and Gamma-prime phase. These phases have limited stability and can grow, redistribute, disintegrate, or convert into other phases. Unwanted new phases like σ -phase can be formed over time as well. Some degradation is completely reversible; some is not.

Fretting

Fretting is the wear of components that are in low-amplitude vibrating contact. The slight relative motion creates an ongoing process of diffusion welding and tearing apart of these welds on a microscopic scale.

In many alloys, fine particles are thus torn out of the surface, leading to the typical signs of fretting. Hardness of the alloys is only a factor but not an all-determining parameter. Cobalt-base alloys have better resistance to fretting than nickel-base alloys.

Assessment and basis of modification of existing gas turbine components

In the operation of a gas turbine, good housekeeping is the art of finding the best compromise between limited component lifetime and efficient power output of the gas turbine. In other words, gas turbine (hot-section) components are designed for and will be operated to survive an optimized and limited lifetime. The weakest points of designs will determine the lifetime. By repair or modification of these points, lifetime can be extended.

At the same time, these weakest points are usually concentrated in just a single detail of the entire component. Since most life-limiting processes in gas turbine components are controlled by processes that are based on diffusion kinetics, which, in turn, are highly material temperature controlled, small changes in metal temperature can lead to dramatic extensions of component lifetime. Thus, modifications can usually be small changes with big consequences.

A good impression of the stresses and temperatures of gas turbine components

can frequently be obtained with a straightforward analysis. Metal temperature distribution can be assessed with fair accuracy by determining the ageing of the alloy in various areas. A simple and straightforward analysis can yield a reliable identification of safe zones for repair or modification, critical danger zones, and transition zones. It is obvious that this analysis must be carried out and interpreted conservatively. When first-order calculations indicate borderline combinations of stress and temperature, 3D measurement and finite element calculations are the tools to refine the model. The required technology is sophisticated and available.

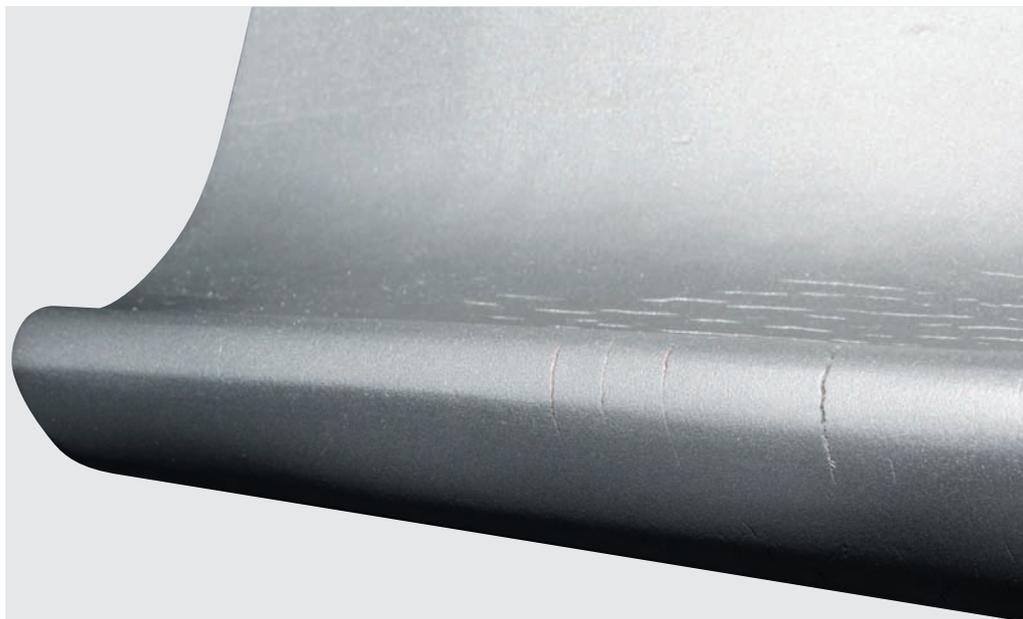
Thorough knowledge of superalloy metallurgy, properties, processing, coating etc. is a prerequisite to undertaking any steps in modifying gas turbine components. Despite that fact, most modifications are a result of straightforward sound thinking and acting. Solutions can address a very specific case or a wide array of problems.

Examples of modifications for longer lifetime

Thermal-barrier coatings (TBC) in industrial gas turbines are plasma-sprayed ceramic coatings that act as an insulator between hot gases and cooled components. A TBC not only reduces average metal temperature, but also reduces steep thermal transients.

TBCs were introduced for combustion components many decades ago. Because of their surface roughness, gas turbine original equipment manufacturers (OEM) and users were reluctant to introduce them on airfoil surfaces. When increasing power and efficiency requirements led to higher firing temperatures and internal cooling technology could not keep pace, and when the requirement to achieve acceptable lifetimes from components grew to a nearly unachievable level, TBCs were introduced on airfoils. In many cases, lifetime was doubled or tripled, and, surprisingly, few or no effects were found in internal efficiency or power output.

3 Deep thermal cycling cracking in the leading edge of a gas turbine blade.



First stage leading edge damages

The leading edge of a gas turbine blade is exposed to the severest risk of overheating because of the high rate of heat exchange that is caused by the impingement of hot gases. Leading edges, thus, are provided with the majority of the cooling air and are frequently designed as a relatively thin-walled pipe that is cooled by internal airflow.

Despite the large amount of cooling air, leading edges are still vulnerable to overheating and thermal cracking, as is demonstrated by many sets of damaged components. It frequently proves that cracking in a set of components is more pronounced in components with thin leading edges than in the ones with thick leading edges. A thick leading edge will conduct more heat to cooler parts of the airfoil than a thin one. In reverse engineering, component modification to thicker leading edges is more easily incorporated than in repair of existing components although reliable processes are available for the latter as well.



4 Hot Corrosion damage in first stage gas turbine blades.

Lifetime determined by corrosion rate

Cooling air is a scarce commodity in gas turbines. Components that lack cooling will deteriorate within an unacceptably short period of time. When lifetime is determined by the corrosion rate of the base material, one option is to simply increase wall thickness of that component. This is well feasible but not straightforward, since the external dimensions of the profile should not be violated.

Additionally, the available cooling air can be redistributed in such a way that hotter sections will be provided with more cooling air at the expense of cooling air for areas that have already exhibited long lifetimes because of ample cooling.

Example lifetime extension

In the case described here, the modification was more complex than usual. Border conditions were: no changes in total cooling airflow for this component and no changes in the contour of the airfoil were allowed. The original component was produced from uncoated

Inconel 939 and had thin walls at the trailing-edge cooling-air exit slot. The modifications were as follows:

- Internal cavity and the cooling-air exit slot modified to double minimal wall thickness
- Cooling-air impingement insert modified for cooling-air distribution to the hottest sections
- Change of material from IN939 to IN738LC with better resistance to internal oxidation and nitridation
- Application of an oxidation-resistant aluminum diffusion coating

In these components, lifetime was tripled by this combination of actions.

Successful lifetime extension

Many gas turbine hot-section components have a limited lifetime. Oxidation, corrosion, material degradation, and thermal cracking are the usual lifetime determining processes. A limited lifetime can be caused by deterioration of only a detail of a component.

A thorough analysis and understanding of the mechanism can lead to accurate pinpointing of that detail and to ways to improve lifetime of the component. Improvements can be made on existing service-exposed components as well as in new designs. Lifetime extensions to a multiple of the original lifetime have been achieved.

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