

Article Info

Received: 02 Apr 2016 | Revised Submission: 20 May 2016 | Accepted: 28 May 2016 | Available Online: 15 Jun 2016

Failure Analysis of First Stage Gas Turbine Blade

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ABSTRACT

In last few decades, the operating temperatures of gas turbine engines have been continually increased in order to achieve higher and higher power and efficiency. During the operation of power generation gas turbines, the blade and other components of hot gas path undergoes service induced degradation, which may be neutral or accelerated due to different causes. The degradation or damage may have a metallurgical or mechanical origin and results in reduction of equipment reliability and availability. It also increases risk of failure occurring. Also, due to blade material metallurgical deterioration, the material creep, fatigue, impact and corrosion properties decrease. There are different factors which influence blade lifetime as design and operation conditions but the latter are more critical.

Keywords: Gas Turbine Blade; Creep; Corrosion; Fatigue.

1.0 Introduction

In order to identify the root causes of blade failures, a complete investigation integrating both mechanical analyses and metallurgical examination has been carried out. In gas power plants, Turbine blades are most critical component of gas turbine. During event of their failure, the power plant shut down. This can cause economic loss. Therefore, it become necessary to conduct the detailed analysis of failure of gas turbine in order to get better understanding of the cause of failure problem and to increase the reliability and efficiency of the system. Turbine blades are subjected to very strenuous environments inside a gas/steam turbine. They face high temperatures, high stresses, and a potentially high vibration environment. The type of damage which occurs in gas turbine blades after a service period can be divided into External and internal surfaces damage (corrosion, oxidation, crack formation, erosion, foreign object damage, fretting) and internal damage of microstructure as γ' phase, Ni₃ [(Al, Ti)], phase aging (rafting), grain growth, grain boundary creep voiding, carbides precipitation and brittle phases formation.

During the operation of power generation gas turbines, the blades and other elements of hot

gas path suffer service induced degradation which may be natural or accelerated due to different causes. The degradation or damage may have a metallurgical or mechanical origin and results in reduction of equipment reliability and availability. It also increases risk of failure occurring. Also, due to blade material metallurgical deterioration, the material creep, fatigue, impact and corrosion properties decrease. In service, blade material deterioration is related to the high gas temperature, high steady state load levels (centrifugal load) and high thermal transients loads (trips, start-ups and slowing downs).

Vardar et al. [1] investigated a 40 MW gas turbine blade made of Udimet 500 after 8000 hrs in service and found that the cause of failure are intergranular cracks which started during exposure to high temperature.

The cracks initiated from the grain boundaries and propagated to the critical length to result in catastrophic fracture. Barella et al.[2] has analyzed a third stage turbine blade failure made of nickel-based super-alloy IN738 after 22,400 operating hours in the 150 MW unit of a thermal power plant stated that after observing the turbine blade it was found that the fracture on the turbine blade is located at the top fir-tree root and the fracture surface exhibits two characteristic zones:

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the first zone shows slow and stable crack growth with crystallographic faceted cracking and striation formation, and the second shows inter-dendritic fracture, typical of final stage failure. This turbine blade failure must be attributed to fretting fatigue phenomena as a result of contact between the nickel-based blade fir-tree and the steel-based rotor disk. Z. Mazur et al. [3] analyzed a 70 MW gas turbine first stage blade made of nickel-base alloy IN738LC after 24,000 hrs of operation conclude that the failure was attributed to thermal fatigue with a significant contribution of creep. Patil et al.[4] has investigated a second stage gas turbine blade made of nickel-base alloy IN738LC after 73,500 hrs in service by metallurgical and mechanical examinations and observed a serious pitting was occurred on the blade surfaces and there were evidence of fatigue marks on fracture surface. Khajavi et al. [5] has reviewed different types of hot corrosion with their microscopic characteristics, and a case study on the first stage blades of a GE-F5 gas turbine. Gallardo et al. [6] has found that first-stage blades of a gas turbine had suffered a severe deterioration after around 10,500 hrs service while the expected service life was 40,000 hrs. FARHANGI et al. [7], has investigated a second stage turbine blade in a 32 MW unit in a thermal power plant. Jianfu et al. [8] has investigated fatigue failures of turbine blades by mechanical analysis. Poursaeidi et al.[9] has investigated a second stage gas turbine blade made of nickel-base alloy IN738LC after 73,500 hrs in service.

The blade failure can be caused by a number of mechanisms under the turbine operating conditions of high rotational speed at elevated temperature. In general, there are three possible damage mechanisms which effect turbine blades are: High temperature corrosion, Fatigue including both high cycle fatigue (HCF) and low cycle fatigue (LCF), and Creep.

2.0 Fatigue:

The blade attachment at the fir-tree joint in gas turbine engines is subjected to high cycle fatigue condition that involves high frequencies and vibration type loads, hence failed due to fretting fatigue. During fretting fatigue process, crack will nucleate and propagate according to severe stress

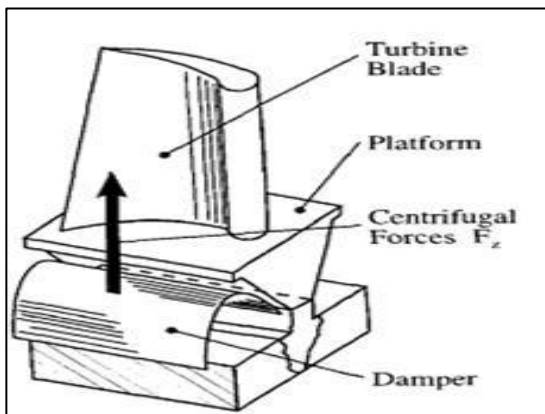
gradients that are generated from the effective shape of contact, co-efficient of friction and applied loads. Initially fretting cracks are very small, but lead to catastrophic failure of the components. There are different signs which show the presence of fretting fatigue. These are: presence of wear track on contact surface, formation of wear products on contact surface and at crack opening, micro plastic deformation in nucleation site, nucleation in vicinity of wear tracks, slant orientation of crack in nucleation region. Eliminating or reducing slip between mated surfaces is the only method for preventing fretting fatigue. And it must be accomplished during design process. Another method to reduce fretting fatigue is shot peening, by inducing compressive stress under the surface to increase fatigue strength.

In a study conducted by the Scientific Advisory Board of the US Air Force targeted high-cycle fatigue (HCF) as the single biggest cause of turbine engine failures. HCF results in rapid, essentially unpredictable failure due to fatigue crack propagation under ultrahigh frequency loading. Furthermore, Initiation of cracking takes place due to small defects which are caused by fretting and impact by foreign particles. Gas turbine components experience high frequency (>1 kHz) vibrational loading due to transient airflow dynamics. This vibratory loading is often superimposed on a high mean stress. Because of the very high frequency of loading, even cracks growing at slow per-cycle velocities propagate to failure in a short period of time. For this reason, it is necessary to operate HCF critical gas turbine components below the fatigue crack propagation threshold (ΔK_{TH}), such that crack propagation cannot occur.

To increase the high cycle fatigue (HCF) life of turbine blades against large amplitudes vibrations inter-blade friction dampers are often incorporated into the bladed disks. The principal parameters that govern the performance of friction dampers are: contact load, roughness of rubbing surfaces, level of external excitation, location of contact region, mass and stiffness of the device. Internal material damping has proved to be of less importance in controlling blade vibrations due to low damping ratio of the materials that may be used and is sometimes neglected in the

computations. The aerodynamic damping is greatly affected by the aspects of the blade section. This damping may be negative, i.e., adding energy to the motion of vibration, and causing flutter of the blade. The third mechanism of damping is friction damping. Friction damper uses dry friction to dissipate energy and thus reduces the stresses. Friction damping takes place whenever two contact surfaces experience relative motion. The centrifugal force arising from the rotation of disc forces the damper against the platform and energy is dissipated, when there is slip motion at contact surfaces.

Fig 1: Gas Turbine Blade



3.0 Corrosion:

During services of gas turbines, the air and fuel encountered with corrosive contaminants that result in serious hot corrosion problems. A wide range of fuel used in gas turbines ranging from clean gas to crude oil which contains sulphur, sodium, potassium, vanadium, lead, and molybdenum as contaminants. The airborne pollutants entering with the inlet air includes sodium, sulphur, chlorine and calcium. Impurities which are present in the fuel and the air can lead to the deposition of alkali metal sulfates on the blades which results in the hot corrosion attack. When the alkali salt attack on the surface, initially there is no reaction because it is coated with a protective oxide layer. For oxidation, this protective layer must be destroyed. This can be done by four ways: (i) Dissolution of protective oxide layer by using salts, (ii) Mechanical disruption of the oxide either by

erosion, thermal cycling and by elastic strain of the substrate putting the oxide in tension, (iii) By diffusion of sulphur through the oxide layer until chromium rich sulfites form within the metal, (iv) A local reducing environment during ignition may form due to incomplete burning of fuel. Such reducing atmosphere can damage the protective oxide layer.

3.1 Hot corrosion:

Hot Corrosion is defined as an accelerated corrosion which results due to the presence of salt contaminants Na_2SO_4 , NaCl , and V_2O_5 that combine to form molten deposits, which further damage protective oxide layer. Hot Corrosion is of two types: (1) High Temperature (Type I) and (2) Low Temperature (Type II). During service, one more type of corrosion is observed which has features of both (HTHC) and (LTHC) and hence the name given is Transition hot corrosion.

3.1.1 Hot corrosion (Type I):

It is an extremely rapid form of oxidation that takes place at temperatures between 8150°C and 9500°C in the presence of sodium sulphate. By the reduction of sodium sulphate, sulphur is released. This sulphur diffuses inward and then reacts with chromium from the substrate to form chromium sulphides

Sodium sulphate = Sodium + Sulphur + Oxygen
(From air and Fuel)

Sulphur + Chromium = Chromium Sulfides

As corrosion proceeds, the sulphides are converted to complex unstable metal oxides and sulphur thus released diffuses more deeply into the substrate where it forms more sulphides.

By using an electron beam analyzer, it is found that sulphide particles of chromium and titanium are present in a region below the surface scale which consists of chromium oxide Fig 2(a).

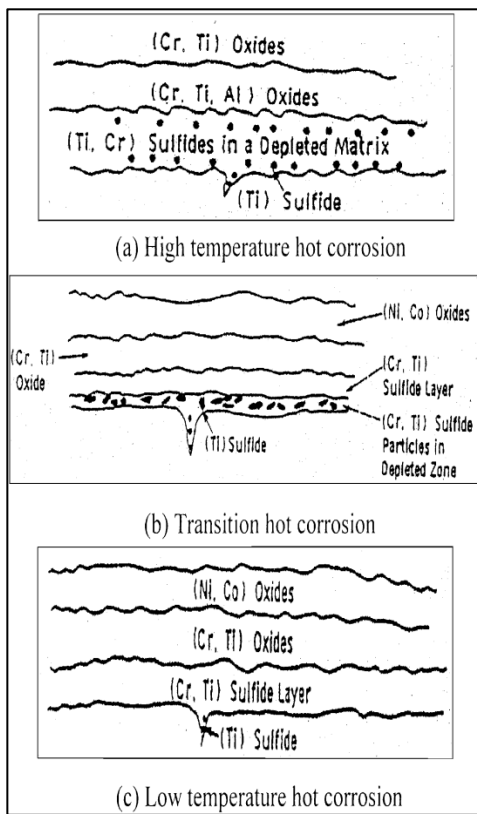
3.1.2 Hot corrosion (Type II): It takes place in the temperature range of 5930°C to 7600°C . If the conditions are correct, this type of corrosion can be very aggressive. It results due to low melting eutectic compounds which are formed by the combination of sodium sulphate and some of the alloy constituents such as Nickel. Low temperature corrosion characteristically shows no inter-granular

attack and no subscale sulfite particles but shows layered type of corrosion scale.

By using an electron beam analyzer, it is found that sulfide particles of chromium and titanium form a continuous layer and the surface scale contains un-protective oxides of Nickel and Cobalt Figure 2(c).

The temperature at the platform region is lower as compare to the airfoil and hence these regions could be prone to type II hot corrosion attack. It is mainly confined to trailing and leading edge regions.

Fig 2: Types of Hot Corrosion



3.2 Transition type:

During services, there are corrosion found which has features of both HTHC and LTHC. Hence the name given to this type of corrosion is Transition Hot Corrosion. By using an electron beam analyzer, It is found that the sulfides of chromium and titanium are increasingly agglomerated into large interconnecting sulfide networks and surface scales contains the oxide of Nickel and Cobalt Fig 2(b).

In order to make gas turbine components oxidation and corrosion resistant, coating must be provided. In accordance to the demand to increase turbine inlet temperatures and thus cycle efficiencies, ceramic insulating coatings can be applied to decrease the temperature of the hottest parts of the turbine components by up to 1700C. Oxidation and corrosion resistant coatings which are applied to the gas turbine engine components are of two types. These are (1) Diffusion Coating and (2) Overlay Coating.

3.2.1 Diffusion coating:

In diffusion coating, an inter diffusion zone is formed between the substrate and the coating. Diffusion coating is formed by diffusion of one or more elements into the surface of the metal to be protected. Typical diffusion coatings are simple aluminide and chromium or platinum modified aluminide coatings.

They are more commonly referred to as diffusion coatings since their application involves inter diffusion between deposited Al or Cr and the substrate onto which they are coated. For example the aluminising of a nickel-based superalloy gives rise to a coating of generic composition NiAl (β -nickel aluminide).

3.2.2 Overlay coating:

In Overlay coating, no inter diffusion zone is formed between the substrate and the coating as formed in diffusion coating.

Overlay coatings are basically coatings of specific composition applied directly on to the surface to be protected. These are deposited by using thermal spray like Argon shrouded plasma spray (APS) or Low pressure plasma spray (LPPS) or Electron beam physical vapor deposition (EBPVD). LPPS gives superior microstructure and mechanical properties but is expensive.

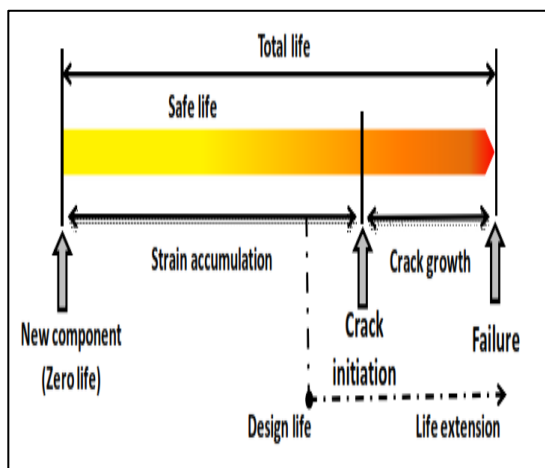
Typical overlay coatings are MCrAlX type where M is usually nickel or cobalt; X is Y, Si, Ta, Hf, etc. which is mostly less than 1% by weight.

4.0 Creep

Creep behavior is one of the most critical factors determining the integrity of elevated temperature components, because such components

can slowly and continuously deform under constant stress over a period of time. The temperature and time dependence of creep deformation indicates that it is thermally activated process. This deformation is the result of Dislocation climb, Vacancy Diffusion, and Grain Boundary sliding. Creep leads to a fracture in components at static stress. Creep is the largest potential problem in applications involving high temperatures and high stress. Betten have described how micro-cracks begin on the surface and propagate until they link into macro-cracks and become visible at the tertiary stage of creep as shown in Fig.[3].

Fig 3: Creep Due to Life Span of Hot Section Components Deformation



The turbine blades made by nickel base super alloy. The Ni-base super alloy has high creep resistance due to precipitation hardening. The micro-structural changes occur due to blade operation at high temperature include irregular growing of γ' particles (rafting) and formation of carbides in grain boundaries and matrix. This leads to alloy creep properties reduction.

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