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A Review on Failure Analysis of Turbine Blades of Aero Gas Turbine Engine

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ABSTRACT

Almost all commercial electrical power on earth is generated with a turbine, driven either by wind, water, steam or burning gas. Turbine blades are subjected to very strenuous environments inside a gas turbine. They face high temperatures, high stresses, and a potentially high vibration environment. All these factors can lead to blade failure, resulting in catastrophic failure of turbine. In the event of turbine blade failure, turbine does not work and this leads to shutdown of power plant from one to four weeks or longer, depending on the extent of the damage and the procedure used to make the machine operational again, which results in economic loss and service to mankind also stops. For each day of a forced outage, a utility could lose hundreds of thousands of rupees in electrical power.

The external and internal surface damages include corrosion, oxidation, crack formation, erosion, foreign object damage and fretting. The internal damage of microstructure include γ' phase, $CoNi_3$ [(Al, Ti)] phase aging (rafting), grain growth, brittle phases formation, carbides precipitation, creep and grain boundary void formation. These damages produce dimensional change which results in increase in operational stress that leads to deterioration in turbine efficiency. The deterioration of blade material is related to the high gas temperature, high steady state load levels (centrifugal load) and high thermal transient load (trips, start-ups, start downs). In this research, a review of common failures due to metallurgical defects found in gas turbine discussed is presented.

Keywords : Turbine blade, corrosion, fretting fatigue, High cycle fatigue, Overheating.

I. INTRODUCTION

A study was conducted by Blotch (1982) for gas turbine failures and concluded that turbine blades and rotor component contributed to 28 percent of primary causes of gas turbine failures, whereas 18 percent is due to faults in turbine nozzles and stationary parts. Another study was done by Dundas (1994) for gas turbine losses and observed that creep, high cycle fatigue (HCF) and turbine blade cooling related failures added 62% of the total damage costs for gas turbines. In the year 1992, another study was conducted by Scientific Advisory Board (SAB) of the United States Air Force and it was concluded that high cycle fatigue (HCF) is the single biggest cause of turbine engine failures (Ritchie et al., 1999). The degree of blade material deterioration for individual blade differs and it depends on several factors such as total service time, operational conditions, manufacturing process and history of turbine. The common failures found in gas turbine blades due to metallurgical defects are discussed and illustrated.

II. WHAT IS FAILURE ON TURBINE BLADE

Turbine blades are subjected to very strenuous environment inside a gas turbine the phase high temperature high stresses and a potentially high vibration environment all three blade factors can lead to blades failures which can destroy the engines and turbine blades are carefully designed to resist those condition. Turbine blades are subjected to stress from centrifugal force (turbine stages can rotate at tens of thousands of revolution per minute and fluid forces that can causes failure yielding or creep failure.

III. CAUSES OF FAILURE

Different failures of blades made from super alloys may be observed during gas turbine plant testing and operation. The cause of these failures is usually identified both by metallographic methods (micro structural studies, fractography, X-ray crystal analyses), bench and laboratory strength tests, and by strength calculation methods, including nonconventional methods. Long-term gas turbine operation leads to the structural degradation of super alloy blades—there is a change in a number, shape and size of γ'-phase particles and in carbide amounts, distribution and composition. The formation of close-packed topological phases (σ, μ, λ-phases) can also be observed. In a number of cases, the structural degradation blades, including those manufactured from single-crystal and directional-solidified alloys. In long-term operation, such cracks also form on blades made from wrought hightemperature alloys. Based on the metallographic studies of micro-crack propagation in wrought alloys at elevated temperatures, a diagram has been developed in order to predict a type of alloy rupture depending on the temperature and frequency of cyclic loading. The diagram allows diagnostics to be made of blade damage detected in operation.

IV. CORROSION

For more than 80 years, corrosion failure of machine components and structures has been studied. From the study, it is observed that maximum outages in the gas turbine power plants are due to corrosion fatigue failure of turbine blades. Many researchers have done metallographic and fractrographic analysis of failed turbine blades and concluded that chemicals compounds such as oxide, chromium sulfide and complex sulfides play significant role in reducing fatigue strength of turbine blades. Gladys et al., (1999) have investigated a rotor blade made of Ni based super-alloy (AMS 5704) having wear resistant Cr-Ni coating. They have observed deposition of hard catalyst on the shroud and concluded that the blade failure occur due to erosion and high temperature sulfidation corrosion. Eliaz et al., (2002) have studied macroscopic and microscopic characteristics of Type I (HTHC-high temperature hot corrosion) and Type II (LTHC-low temperature hot corrosion). They have described different practical approaches to minimize hot corrosion. Khajavi et al., (2004) have discussed different types of hot corrosion, i.e. HTHC (High temperature hot corrosion), LTHC (Low temperature hot corrosion) and transition type, and investigated a first stage blade of a GE-F5 gas turbine. They have concluded that the blade has failed by both types of hot corrosion but HTHC was dominant. Gallardo et al., (2002) have investigated a gas turbine blade made of nickel super-alloy CMSX4. They have observed that at high temperature, coating on the surface deteriorated due to wear. The unprotected surfaces suffered with high temperature hot corrosion (HTHC). Attarian et al., (2013) have collected a gas turbine blade made of IN738LC nickel base super-alloy, which was failed after rendering service for 1500 hours. They have found that the blade failure took place by dissolving the γ' in matrix due to exposure of high temperature and pressure. Das et al., (2003) have investigated a stainless steel turbine blade of a 220 MW thermal power plant. They have observed several pits on the surface and the presence of chloride salt in these pits was responsible for crack initiation by crevice corrosion and concluded that the blade failed due to corrosion –fatigue mechanism. Xie et al., (2006) have investigated the premature tip cracking of the high pressure first stage gas turbine blade. They have found that the premature crack was due to corrosive/oxidative service environment and high thermal stresses. They concluded that coating having both oxidation and abrasion resistance should be applied in blade tip to avoid the problem. Bhagi et al., (2013) have studied a fractured low pressure 110 MW steam turbine blade made of chrome alloy X20Cr13. They have found the oxides of silicate and sodium on fractured surface, which leads to the formation of corrosion pits and concluded that the blade failed due to corrosion fatigue. Patil et al., (2007) has investigated a failed second stage gas turbine blade made of nickel based super-alloy IN738LC. They have found that crack initiated at the leading edge due to hot corrosion and propagated by fatigue mechanism finally resulting in complete fracture of the turbine blade. Corrosion is reduced to great extent by providing coatings on surface of turbine blade and proper cleaning of cooling holes. Secondly, proper selection of alloy element for manufacturing of turbine blades is a major concern; the material must be corrosion resistant. Nicholls et al., (2002) have studied smart lay coatings and described that the smartcoat design consists of a MCrAlY base, first enriched in chromium and then aluminium. At high temperature, the coating oxidised to form protective aluminium rich surface layer, which provided reisistance to high temperature oxidation and Type I hot corrosion. The coating also had an intermediate chromium rich interlayer, which permitted the formation of chromia healing areas of Type II corrosion damage. Strawbridge et al., (1997) have studied the oxidation behaviour of air plasma sprayed NiCrAlY coatings at 12000C in 1 atm air. They have observed that a protective alumina layer developed during the early stages, but this layer broke away after prolonged exposure. Turbine blades are normally protected with sophisticated coatings, usually based on chromium and aluminum, but often containing exotic elements such as Yttrium and Platinum group metals to provide resistance to corrosion and oxidation while in service (Carter, (2005)).

V. FATIGUE

Turbine blades are most susceptible to crack formation in regions of contact surfaces, which are exposed to both centrifugal loading and oscillatory vibrations. These mating components are failed due to fretting fatigue. Fretting fatigue results in an increase in tensile and shear stress at the contact surface, which leads to crack initiation and its propagation till failed completely. At elevated temperatures, fatigue cracks have been observed to initiate from grain boundaries, slip bands, pores, twin boundaries or due to cracking of inclusions/precipitates. The majority of turbine failure includes fatigue leading to crack initiation and propagation. The operating conditions of high rotational speed at elevated temperature, corrosion, erosion and oxidation accelerates fatigue failure. Pang et al., (2007) have performed an assessment for finding the effects of microstructure and operating parameters on fatigue crack initiation and short crack growth in powder metallurgy (PM) nickel-based superalloys, at room temperature and at 650 °C. They revealed that, at room temperature, fatigue cracks were observed to initiate from both porosity and slip bands and at 650 °C, only porosity dominated for the initiation of fatigue crack and no slip-band initiation observed. Mazur et al., (2009) have evaluated a last stage, AISI 420 stainless steel blade (L-0) of 28MW geothermal turbine and concluded that blade failure initiation and propagation was due to a high cycle fatigue mechanism, which got accelerated to a high degree by corrosion/ erosion processes that occurred in the blade trailing edge zone. Kim et al., (2011) have investigated a fourth stage blade of a 500 MW steam turbine to evaluate a crack found on the leading-edge vane and observed that the condenser tube had leakage through which the seawater entered resulting in the induction of corrosion pits. These corrosion pits acted as a notch for stress concentration and facilitated crack initiation under cycling loading conditions. The crack propagated inwards by fatigue mechanism due to vibration of blade. Barella et al., (2011) have investigated a third stage turbine blade of 150MW thermal power plant, made of nickel-based super-alloy IN738 which failed after rendering service of 22,400 hrs. They have concluded that the blade failed due to fretting fatigue mechanism. Poblano-salas et al., (2011) have studied a steam turbine blade made up of stainless steel having a crack on the airfoil. They have observed that the fractured surface contained a section of lacing bar and concluded that the airfoil failure took place due to deficient brazing process employed for bonding the component to the lacing bar at the last stage of the turbine. SEM evaluation revealed that crack propagation was due to fatigue mechanism. Kubiak et al., (2006) have investigated a first stage gas turbine blade of 150MW turbine that was failed suddenly due to high vibrations. They have concluded that the low cycle fatigue mechanism generated a crack in the securing pin hole located at the root of the blade and it propagated by excessive thermal stresses inside the body of the blade. The crack started from the pin hole below the blade platform – this meant that the fault was associated with faults in the cooling system. They have suggested modifying the gas heater and the rotor air cooling system to prevent accumulation of the condensate in the gas heater and avoid corrosion of inner surfaces of the pipes using different materials and/or coatings. Liacy et al., (2011) have investigated a first stage blade of 85 MW gas turbine made of Ni base super-alloy Udimet 520 having MCrAlY coating. They have revealed that the formation of a continuous net of carbides on grain boundaries reduced the toughness of the alloy and resulted in a brittle inter-granular fracture. Farhangi et al., (2007) have analyzed a 32 MW second stage turbine blade of a thermal power plant, made of nickel based super-alloy Udimet 500 which failed after rendering service of 50,000 hrs. They have found debris on the contact surfaces of fir tree root and concluded that the blade was failed due to fretting fatigue. Mazur et al., (2005) have investigated a 70 MW first stage gas turbine blade made of nickel based super-alloy IN738LC which failed after rendering service of 24,000 hrs. They have observed cracks in the cooling holes at 0.4mm depth, which penetrated the coating and substrate at high stressed areas of airfoil. They have concluded that the crack initiation and propagation occurred due to fatigue/ creep mechanism at high temperature. They have suggested that the cooling system should be improved to increase the life of blade. Maktouf et al., (2015) have analyzed a first stage compressor blade of a gas turbine generator in a gas treatment plant. They have observed that the cracks are initiated at internal metallurgical anomaly region near the airfoil leading edge and propagated towards mid chord of airfoil till failed completely with high cycle fatigue mechanism. Poursaeidi et al., (2008) have investigated a failed second stage gas turbine blade made up of nickel based super-alloy IN738LC. They have concluded that the crack was initiated due to hot corrosion at the leading edge and propagated by fatigue till the blade fractured completely. Lee et al., (2011) have investigated first stage compressor blades of J85 military aircraft engine made of Ti-6Al-4V, found cracked on blade tangs.

They have concluded that the crack is initiated due to fretting wear on the pinhole surface of the tang and propagated by fatigue mechanism induced from centrifugal load and vibration. Shot peening and ultrasonic impact treatment (UIT) methods are used for treating fretting fatigue. These methods induce compressive stresses under the surface to increase the fatigue strength (Barella et al., 2011). UIT method removes tensile stresses to a great extent. More recently, it has been demonstrated that other surface treatment approaches, such as laser shock processing (LSP) can have a beneficial effect on fretting fatigue performance.

Figure 1: The General View of the First Stage Blade

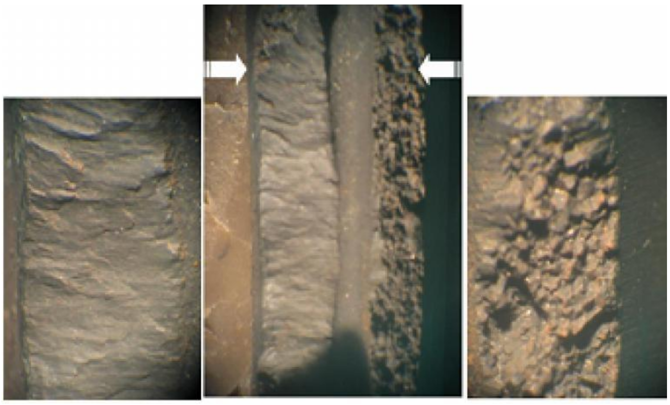

Figure 2 : Stereo Microscopy of the Main Fracture Surface

Thermal fatigue cracks are the characteristic type of edge failures in gas turbine cooled decrease in chromium content in a layer up to 100 mm thick. The analysis of surface layer composition in the region of cracks in blades made from high temperature alloys EI929, ZMI-3 and CNK-7 after operation for 25000 to 35000 h revealed a local increase in sulphur content related to sulfide-oxide corrosion attack (Rybnikov *et al.*, 2005).

VI. STATIC STRESS FAILURE OF GAS TURBINE BLADES MADE OF SUPER ALLOYS

The industrial production of blades by different manufacturers may involve process violations causing a displacement of the mass centre and, as a consequence, the static failure of blades at a fairly high carrying capacity strength margin. Such blade failures were observed in aircraft, marine and stationary gas turbine plants. Thus, 13 cases of rotor blade failures were discovered in a generating gas turbine plant after operation for 1000 to 6000 h. The fractographic study revealed a static cracking mechanism initiated at blade edges. Blade strength calculations were carried out by the finite element method with regard to creep under the conditions of centrifugal forces and mass centre displacement. It was determined that, due to the stress increase at edges and the difficulties associated with stress redistribution during creep, the stresses can reach the material long-term strength values corresponding to rupture life. Another cause of static stress failure of blades is blade overheating related to the departures from normal operating conditions. Such failures are detected by metallographic methods based on metal structural variations throughout the entire blade section.

VII. OVERHEATING

The surface degradation of turbine blade by the formation of needle separation topologically closed packed phase (TCP) occurs due to overheating. This structural instability of the alloy results in decrease in strength and ductility of alloy (Rybhino et al., 2012). Tawancy et al., (2009) have examined the first stage turbine blades and vanes and concluded that the failure of both components took place due to overheating. Overheating promoted creep, resulting in inter-granular cracking that shortened the fatigue life of blades and vanes. Vardar et al., (2007) have investigated a 40 MW gas turbine blade made of Udimet 500. They have observed continuous film of carbides in grain boundaries, which was formed by the transformation of MC type of carbides to M6C type of carbides due to high temperature. Kargarnejad et al., (2012) have analyzed a first stage blade of 3MW gas turbine, made of nickel based alloy Nimonic 80A. They have observed that the blade lost coating at high temperature and concluded that the blade was failed due to oxidation, corrosion, erosion and inters diffusion of coating substrate, which resulted in the degradation of base alloy.

VIII. CONCLUSION

Based on the literature and studies reported above, following conclusions are drawn:

1. The external and internal surface damages include corrosion, oxidation, crack formation, erosion, foreign object damage and fretting. The internal damage of microstructure includes γ' phase, CoNi3 [(Al, Ti)] phase aging (rafting), grain growth, brittle phases formation, carbides precipitation, creep and grain boundary void formation.

2. It is concluded that maximum outages in the gas turbine power plants are due to corrosion fatigue failure of turbine blades. It is concluded that chemicals compounds such as oxide, chromium sulfide and complex sulfides play significant role in reducing fatigue strength of turbine blades.

3. Fretting fatigue results in an increase in tensile and shear stress at the contact surface, which leads to crack initiation and its propagation till the turbine blade failed completely.

4. The majority of turbine failure includes fatigue leading to crack initiation and propagation. At elevated temperatures, fatigue cracks have been observed to initiate from grain boundaries, slip bands, pores, twin boundaries or due to cracking of inclusions/precipitates.

5. The surface degradation of turbine blade by the formation of needle separation topologically closed packed phase (TCP) occurs due to overheating. This structural instability of the blade alloy results in decrease in strength and ductility of blade alloy.

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