Root Causes of Failure in High Pressure Turbine Blades

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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. Around 22% of total global power generation is produced by gas power plants. Turbine Blades of a turbine engine are very prone to damage from flying debris; moreover they also sustain thermal stresses and local overheating on their surface of gases that are coming out from combustion chambers. Due to increase in generating capacity and operating pressure of individual utility units, various new methods have been employed to increase the efficiency of turbines. Recent methods include thin and highly twisted design of turbine blades with low aspect ratio, which results in high levels of vibratory stresses and forces the designers to use higher strength materials. 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 this research work, root causes of failures of high pressure gas turbine blade have been illustrated in detail.**

Keywords: **High cycle fatigue, Fretting fatigue, sulphidation, oxidation, hot corrosion, standby corrosion**

I. INTRODUCTION

The total design capacity of gas turbine power plants in India is about 26699.9MW which is nearly twice of that for the year 2011 in which it was 13711.27 MW *(CEA India, 2017[1])*. Hence, gas power plants are reliable workhouse of the power industry in the developed and developing countries contributing 22% of total global power generation. Modern turbine blades are manufactured by Ni-based super-alloys. The production methods involve directionally solidification (DS) and single crystal (SC) (*Das, 2010 [2]).*

In a directional solidification method, all the grain boundaries are aligned in one direction. The major failure mechanism for gas turbine airfoils involved nucleation and growth of cavities along transverse grain boundaries. During direct solidification, transverse grain boundaries are eliminated, hence turbine blade metal temperature capability has improved. This production method increases the fatigue and creep strength of turbine blade material. In single crystal (SC) castings, all grain boundaries are eliminated from the microstructure and single crystal with a controlled orientation is produced in an airfoil shape. By eliminating grain boundaries altogether improves creep and fatigue resistance.

A study was conducted by (*Blotch, 1982 [3])* 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 [4])* 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. The high dynamic stresses at resonance lead to fatigue problems (*Rao et al., 1991[5])*. It is found that high cycle fatigue alone is responsible for maximum forced outages in the high pressure stages in gas turbines.

II. GAS TURBINE BLADE MATERIALS

In mid-1960, most of first stage turbine blades are made of U-500, which is a precipitation-hardened (gamma prime), nickel-based alloy by the lost wax technique. Now a day, it is used for later stages buckets in selected gas turbines (*Schilke, 2004 [6]*). During 1970s, the increase in blade alloy temperature capability accounted for the majority of increase in firing temperature. This problem is solved, when air cooling was introduced, which decoupled firing temperature from bucket metal temperature. As the blade metal temperature approached 1600°F/870°C range, hot corrosion of turbine blade became more life-limiting than strength. To resolve this problem, protective coatings are introduced. The first thermal barrier coating (TBCs) applied in the 1970s was aluminide coating. In the 1980s, improved ceramic coatings became available. These coatings increased turbine blade temperature capability by about 200 °F (90 °C). The coatings improve turbine blades life almost double in some cases. During the period 1971 to 1984, Nickel based super-alloy IN738 has been used for first stage gas turbine blade as stage 1 bucket material on several GE engines. The alloy has an outstanding combination of elevated temperature strength and hot corrosion resistance and this makes it attractive for heavy duty gas turbine applications. Developments in processing technology have enabled production of the alloy in large ingot sizes. During the 1980s, emphasis turned towards two major areas: improved material technology, to achieve greater blade alloy capability without sacrificing alloy corrosion resistance and advanced highly sophisticated air cooling technology to achieve the firing temperature capability required for the new generation of gas turbines. Subsequently GE has developed the alloy GTD-111, with higher strength levels than 738, but maintaining its hot corrosion resistance. GTD-111 has replaced IN738 as bucket material in different GE engine models (*Schilke, 2004 [6]*).

Table 1: The Chemical composition of super-alloys for blading applications (wt%)

Alloy	Cr	Co	Al	W	Ti	Mo	Ta	Ni
IN738LC	16	8.3	3.4	2.6	3.4	1.75	1.75	62.8
U500	18.5	18.5	3	-	3	4	-	53
GTD111	14	9.5	3	3.8	4.9	1.5	2.8	60.5

III. Root Causes of Failure in High Pressure Turbine Blades

With the increase in generating capacity and operating pressure of individual utility units, various new methods have been employed to increase the efficiency of turbines. The changes in design and use of different types of materials for turbine blades, turbine wheels, compressor blades and coating material, have resulted in increased efficiency and also stresses. Recent methods include thin and highly twisted design of turbine blades with low aspect ratio, which results in high levels of vibratory stresses and forces the designers to use higher strength materials. Turbine blades face high temperatures, high stresses, and a potentially high vibration environment inside turbine. All these factors can lead to blade failure, resulting in catastrophic failure of turbine.
There are various factors responsible for failures of turbine blade are High cycle fatigue, Low cycle fatigue, Thermo-mechanical fatigue, Fretting fatigue, High temperature oxidation, Sulphidation, High temperature hot corrosion (HTHC), Low temperature hot corrosion (LTHC), Transition corrosion and Standby corrosion.

IV. FATIGUE

In the year 1992, a 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., [7]*). The blade vibrations and resonances at critical speed produce high dynamic stresses, which produce high cycle fatigue in turbine blades. The common causes of vibration in blades include nozzle passing frequency wakes, choke, and blade flutter. In the turbine section, airfoils have to function not only in severe vibratory environment but under strenuous conditions of high temperatures, high stresses, corrosion, and thermo-mechanical fatigue. The resonance occurs when the nozzle passing frequency (NPF) of any of its harmonics coincides with any one of the blade natural frequencies. The high dynamic stresses at resonance lead to fatigue problems (*Rao et al., [5]).*

4.1 HIGH CYCLE FATIGUE

The resonance occurs when the nozzle passing frequency (NPF) of any of its harmonics coincides with any one of the blade natural frequencies. Resonant fatigue is considered as an important failure mechanism. If the damping is inadequate for absorption of the periodic input energy, amplitudes and stresses grow until failure occurs by overstress or by propagation of a fatigue crack. High cycle fatigue (HCF) is typically caused by aerodynamic excitations (i.e., nozzle and vane passing frequencies, strut pass frequency) or by self-excited vibration and flutter. High cycle fatigue damage will occur when stress levels are above the fatigue strength. It is also noted that the fatigue strength is severely affected by a corrosive environment. The factors responsible for the growth of vibration at resonance are Magnitude of the exciting force, Damping of blade material, resonant response factor, i.e., a measure of the ability of the blade (or blade packet) to accept energy from the stimulus.

To increase the fatigue life of turbine blades against large amplitude vibrations, blade designs have evolved that utilize insertion of dampers between two adjacent blades that fit inside the blade cavities and produce frictional damping.

4.2 Low Cycle Fatigue

Low cycle fatigue (LCF) occurs as a result of turbine start/stop cycles and is predominant in the bores and bolt hole areas of compressor and turbine disks that operate under centrifugal stresses. It is typically a problem associated with machines that have been in operation for several years.

4.3 Thermo-mechanical Fatigue

Thermo-mechanical fatigue (TMF) is associated with thermal stresses, e.g., differential expansion of hot section components during startup and shutdown, and is particularly severe during rapid starts and full load emergency trips. The stress levels induced may initiate cracks, if they exceed the material yield stress. Temperature variations as high as 360°F (200°C) per minute are often experienced in hot section blading.

4.4 Fretting 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 component 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 it failed completely.

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[8]).* 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.

V. ENVIRONMENT PROBLEMS

During evaluating any blade failure, the working environment must be considered. At high temperature, they are probably attacked from oxidation, corrosion, and sulphidation. The environment alone does not result in catastrophic failures, but act as a catalyst to other failure modes.

5.1 HIGH TEMPERATURE OXIDATION

When nickel based super-alloys are exposed to temperatures greater than 1 000°F (538°C), high temperature oxidation occurs. Oxygen present in the gas stream reacts with the nickel alloy to form a nickel-oxide layer on the airfoil surface. When the blade is subjected to vibration and start stop thermal cycles during operation, this nickel oxide layer tends to crack and spall. This phenomenon may also occur on the inner surfaces of blade cooling passages and result in blade failure. To mitigate this effect, coatings are available and can be applied both on the blade surface and internal cooling holes.

5.2 SULPHIDATION

Sulphidation is a reaction that occurs when sulphur reacts with the protective oxide layer and attacks the base metal. The air ingested by a gas turbine can contain impurities such as $S0_2$, $S0_3$, sodium chloride (salt), and chlorine. As these impurities pass over the airfoil, droplets (slag) of liquid sodium sulfate ($Na_2\ S0_4$) are formed. Under this slag, the protective oxide layer is broken down causing very serious damage. Sodium sulfate is highly corrosive causing deep stress riser pits in the airfoil, which may then develop into cracks (*Boyers, 1975 [9] and DeCresecente, 1980 [10]*).

5.3 HOT CORROSION

Hot section parts are often subject to combined oxidation and sulphidation phenomena, referred to as hot corrosion. Two types of hot corrosion are identified as high temperature hot corrosion and low temperature hot corrosion. One more type of corrosion is observed, which has features of both (HTHC) and (LTHC) and hence the name given is transition hot corrosion.

(i) High Temperature Hot Corrosion (HTHC)

High temperature hot corrosion takes place at temperatures between 815^0C and 950^0C 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 if forms more sulphides. A denuded zone of base metal is found along with inter-granular attack and sulfide spikes.

(ii) Low Temperature Hot Corrosion (LTHC)

Low temperature hot corrosion takes place in the temperature range of 593^0C to 760^0C. 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. 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.

(iii) Transition Corrosion

Transition corrosion has features of both HTHC and LTHC. It is found that the sulfides of chromium and titanium are increasingly agglomerated into large interconnecting sulfide networks and surface scales contain the oxide of Nickel and Cobalt. Coatings are commonly used to mitigate hot corrosion problems.

(iv) Standby Corrosion

Standby corrosion occurs during a turbine shutdown and is the result of air moisture and corrosives being present in the machine. Crevice corrosion occurs, when corrosion products, which accumulate in the blade attachment areas act as abrasives and increase clearances. In the presence of corrosives possibly from airborne salt, uncoated airfoils frequently develop corrosion pits, which may then develop into cracks *(Sohre, 1975 [11])*.

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.

CONCLUSIONS

In this work, root causes of failures of high pressure gas turbine blade have been discussed and illustrated. The following conclusions are drawn:

1. Turbine blades face high temperatures, high stresses, and a potentially high vibration environment inside turbine. All these factors can lead to blade failure, resulting in catastrophic failure of turbine.
2. It is found that high cycle fatigue alone is responsible for maximum forced outages in the high pressure stages in gas turbines.

3. 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 component are failed due to fretting fatigue.
4. It is observed that the maximum failures in high pressure gas turbine are due to corrosion failure of turbine blades.

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