International Journal of Engineering Research and General Science Volume 6, Issue 3, May-June, 2018
ISSN 2091-2730

A Review on Gas Turbine Blade Failure and Preventive Techniques

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Abstract– With the increase in demand for power supply and more efficient turbojet engines, gas turbine designing is being pushed to its extremities. Turbomachines are becoming larger as compared to the machines of past decades. Due to increase in size, the cause and chances of failure have also increased. Gas turbine blade is the component which is exposed to extreme operating condition, thus experience different failure modes. Constant mechanical and thermal stresses act on different sections of blade. Newer super-alloys with enhanced metallurgical properties are being developed and tested to counter the stresses acting on the blades. Advance additive manufacturing techniques are used to produce next generation super-alloys. Failure due to mechanical and metallurgical anomalies are indirectly related to the high operational temperature and can be corrected up to a certain limit. Thus thermal protection is required for blades. Advance cooling techniques and coatings are being used for this purpose. Different literatures were combined to compile all the data analysed on blade failure and the preventive techniques being used.

Key Words– Gas turbine blades, Erosion, Fretting fatigue, Thermal stresses, Super-alloys, Hot corrosion, Film cooling, thermal barrier coating,

1. NOMENCLATURE

k_1 = Material constant

$f(\beta_i)$ = Empirical function of particle impact angle

V_{ti} = Tangent component of incoming particle velocity

V_{tr} = Rebound particle velocity

$f(V_{ni})$ = Component of erosion due to normal component of velocity

E = Erosion rate

K = Von Karman constant

ε = Eddy diffusivity for momentum

l = Mixing length

δ = Boundary layer thickness

P = Row spacing of coolant holes

D = Van Driest damping function

B_r = Blowing ratio

x = Stream wise distance from point of injection

y = dimensionless distance of first point off the blade surface

2. INTRODUCTION

A basic design (fig 1.) of gas turbine setup consists of compressor to increase the air pressure, combustion chamber where fuel is ignited with incoming air flow to increase the thermal and thus kinetic energy of the gases and turbine to produce mechanical output in form of shaft work. Gas turbines are used commonly for power generation and in air-breathing jet engines to power compressor [1]. To yield more output, the design and size of the turbines are increasing drastically resulting in increased stresses on the turbine blade.

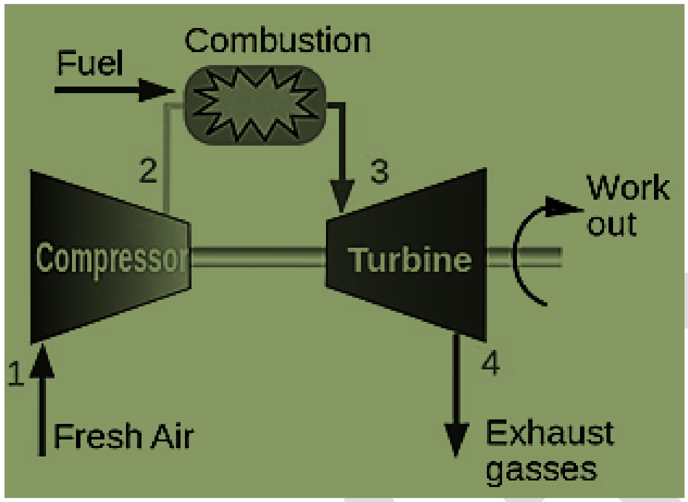

Fig 1. Gas turbine
(https://www.turbinesinfo.com/gas-turbines/)

Turbine blades have to face large amount of vibrations due to critical operating conditions involving high rotary motion at tremendously high temperatures [2,3]. These factors result in common mode of turbine blade failure. Efficiency and the blade reliability reduces mainly due to mechanical and/or metallurgical anomalies such as fatigue, creep, corrosion and erosion. Other factors may be airborne pollutants, foreign object damage or poor manufacturing or irresponsible operating. Corrosion and fatigue being of main concern are most analyzed to improve the durability and enhance the operational life of the turbine blades. The material used for gas turbine blades should be hardened, heat resistant with very high melting point and corrosion resistant, thus cobalt-based and nickel-based super-alloys are mainly used [4].

Further to counter thermal stress, advanced cooling techniques like film cooling are being developed and used [5]. The purpose of this paper is to compiles all the major modes of turbine blade degradation leading to failure, preventive methods presently being used and highlight the recommended areas for future study.

3. MODES OF FAILURE AND BLADE DEGRADATION

Gas turbine blades are subject to extreme condition due to which the blades degradation occur. Degradation may be service induced which might be accelerated due to different factor. Damages may occur due to mechanical behavior of the material or the metallurgical properties influencing the blade life time [1,4]. Due to centrifugal and oscillatory actions at component contact, crack formation is found to be significant that this place [6].

3.1 Erosion

Removal of material from the surface by the action of solids or fluids moving in contact with that surface at high velocity resulting in a faster material loss than the expected duration is called *erosion*. Flow sometimes is accompanied by unwanted solid particles that cause cutting and deformation to not only turbine blades but other components of gas turbine also. Erosion in gas turbine blade have been a source of concern since last decades as the designing, efficiency and the economic aspect depend greatly on this factor [7]. I. Finnie [9] stated in his study that erosion is a complex function of particle velocity, angle, material and target properties. Simply, by applying the Grant-Tabaoff erosion model, the erosion of ductile metals and their alloys can be predicted. Assuming the dependency of erosion process on amplitude of angular impingement, the following equation is derived [9]:

$$E = k_1 f(\beta_i)(V_{ti}^2 - V_{tr}^2) + f(V_{ni}) \quad (1)$$

Considering the suction side of rotor blade i.e. the side of blade where the impact angle of striking trapped particle is higher than the maximum erosion angle, erosion rate can be reduced by increasing the mass flow. Whereas, the erosion rate is directly influenced by the rotor's rotational speed as the particles entering rotor domain directly hit the pressure side of the blade [10].

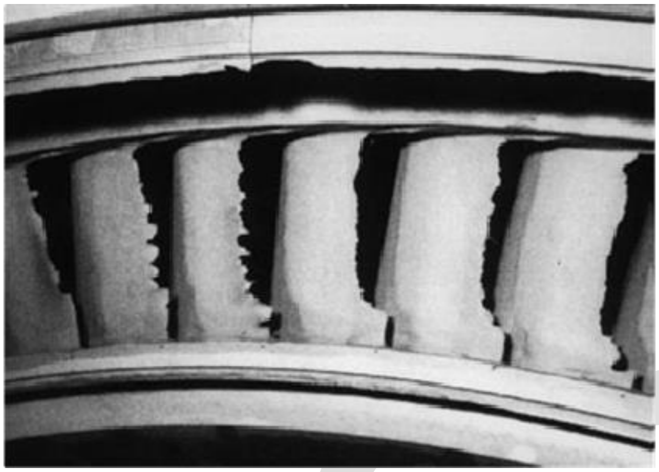

Fig 2. Turbine blades erosion

(https://www.researchgate.net/figure/Severe-erosion on-suction-side-of-steam-turbine-blades_fig2_276490146)

3.2 Fatigue

Fatigue is the weakening of a material due to repeated cycling loads or number of stress cycles it can survive. It is directly related to material properties. High cycle fatigue in turbine blades is one of the main cause of fatigue failure. Estimation of a blade's fatigue life can be made if the stresses acting on the blade and the material properties are known [1]. Blade failures due to fatigue are categorized as high cycle fatigue (HCF) and low cycle fatigue (LCF) [11,12]. Low cycle fatigue is due to stress applied on a body, high enough to produce plastic deformation whereas high cycle fatigue is characterized by the stresses for which S-N curve can be determined [13].

Point that experiences centrifugal and oscillatory vibration, such as component contact for example the region where blades are attached to the disk, are most vulnerable locations for cracking due to fatigue. A significant reduction in fatigue life is caused due to the micro slip experienced by the contact surface when subjected to fatigue. This is known as fretting fatigue. Fretting fatigue is the common cause for increased tensile and shear stresses which further leads to origin of crack, its growth and thus fracture [6]. Propagation of fret crack depends on the stress gradient, shape of contact, coefficient of friction and load applied. Compressor blade root joints are generally coated with Cu-Ni-In for fretting fatigue resistance [14].

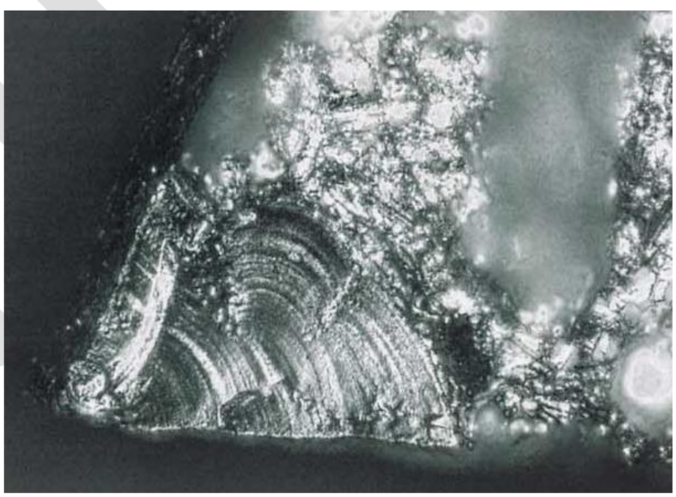

Fig 3. Crack propagation due to fatigue

(An investigation of fatigue failures of turbine blades in a gas turbine engine by mechanical analysis, Engineering Failure Analysis 9 (2002) 201–211)

3.3 Thermal stresses

Large amount of thermal stress is experienced by the turbine blades due to direct exposure to high temperature gases [15]. Components of first stage of turbine are exposed to large amount of thermal loads resulting in creep and thermal fatigue [16]. Particularly, the blade tips experience large thermal loads due to leakage of flow through the gap between the shrouded casing and the blade tip, increasing the chances of cracking. Large pressure gradient between the pressure side and suction side of blade results in acceleration of leak flow which leads to thin boundary layer formation and elevated heat transfer rate. This increases the turbine power loss and decreased efficiency [15]. Failures of even single crystal directional solidified alloy is majorly due to cracks caused by thermal fatigue. Alloy failure depend on the cyclic loading at elevated temperature [6].

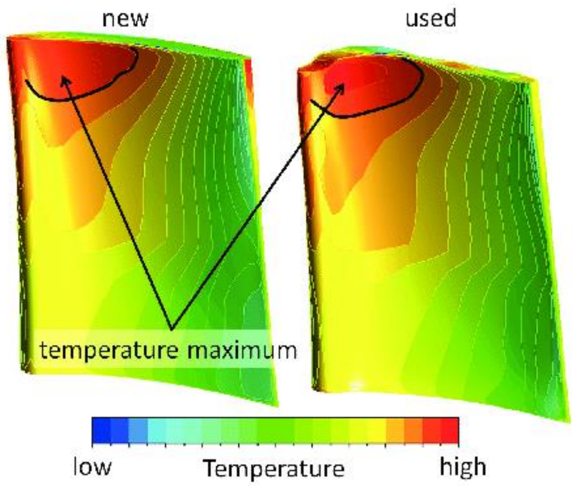

Fig 4. temperature variation on different section of gas turbine blade

(https://www.researchgate.net/figure/Total-pressure-and-temperature-distribution-on-the-new-and-used-turbine-blade_fig2_314197784)

Rhee and Cho [17,18] used a low speed turbine cascade to study the blade tip heat transfer characteristics. Coefficients of heat transfer at tip were found out to be 1.7 times higher compared to blade surface and shroud. As a consequence of reduction in leakage flow caused by the relative motion of case, the heat transfer at the stationary care was 10% more than rotatory case. Study of relation between rim height, tip clearance and heat transfer was done by Park et al. [19,20] which concluded that heat transfer is directly proportional to blade tip clearance and inversely proportional to rim height.

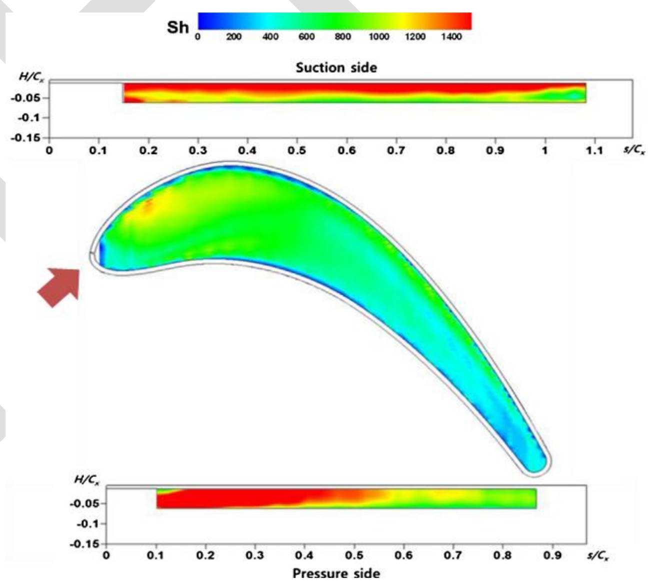

Fig 5. Heat transfer distribution on the tip surface and inner rim surfaces

(Heat transfer and film cooling effectiveness on the squealer tip of a turbine blade, Jun Su Park, Dong Hyun Lee, Dong-Ho Rhee, Shin Hyung Kang, Hyung Hee Cho, Energy 72 (2014) 331-343)

New heat resistant materials are being developed for replacing the current materials. Some of the examples are IN617, TOS1X-I and IN740 [21].

3.4 Material

Super-alloys are used for the application in high temperature operations and can be categorized by the base metal used: Nickel-based alloys, Cobalt-based alloys and Iron-based alloys. Super-alloys are used due to their excellent strength even at very high temperatures. Ni-based and cobalt-based super-alloys are mainly used for the fabrication of gas turbine blades. *IN738LC* is a nickel-based super-alloy with exceptionally high temperature and oxidation resistant properties. The alloy is strengthened by precipitating γ phase [7]. Hardness of IN738LC is due to fcc g-Ni matrix strengthened by solid solution and fine precipitations. Because of its alloying constituents and high g- γ, IN738LC is difficult to weld. Some more nickel-based super-alloys are developed such as IN718, IN6225, Hastelloy X, Waspalloy. Selective laser melting (SLM) can be used to improve tensile strength of IN738LC. Magnetic parts can be directly made using the additive manufacturing technique of selective laser melting [22].

Nickel-based single crystal super-alloys are divided further on the era they were developed in. First generation Ni-based alloy constituting mainly of Cr, Co, Mo, W, Ti and Ta. Cr is essential for hot corrosion resistance, Co and Mo are used due to their property of fcc matrix solid solution strengthening elements. Addition of *Rhenium* produced second generation alloy (Fig. 6) such as PWA1484, Rene N5, CMSX-4, SMP14. Third generation alloys (Fig. 7) like CMSX-10 and Rene N6 were developed by General Electric. New generation of alloys such as MC-NG, TMS75, TMS80 have been developed by Japan and France which show very high creep resistance and less density compared to third generation alloys [23].

Alloy	Cr	Co	Mo	Re	W	Al	Ti	Ta	Nb	Hf
CMSX-4	6.5	9	0.6	3	6	5.6	1	6.5	–	0.1
PWA 1484	5	10	2	3	6	5.6	–	8.7	–	0.1
René N5	7	8	2	3	5	6.2	–	7	–	0.2
SC180	5	10	2	3	5	5.2	1	8.5	–	0.1
SMP14	4.8	8.1	1	3.9	7.6	5.4	–	7.2	1.4	–
MC2	8	5	2	–	8	5	1.5	6	–	–

Fig 6. Chemical compositions (wt.%) of second generation Ni-based super-alloys for single crystal blades.

Alloy	Cr	Co	Mo	Re	W	Al	Ti	Ta	Nb	Hf
CMSX-10	2	3	0.4	6	5	5.7	0.2	8	0.1	0.03
René N6	4.2	12.5	1.4	5.4	6	5.75	–	7.2	–	0.15
Alloy 5A	4.5	12.5	–	6.25	5.75	6.25	–	7	–	0.15
TMS-75	3	12	2	5	6	6	–	6	–	0.1
TMS-80	2.9	11.6	1.9	4.9	5.8	5.8	–	5.8	–	0.1
MC-NG	Patent pending									

Fig 7. Chemical compositions (wt.%) of third generation Ni-based super-alloys for single crystal blades.

3.5 COROSION

Unwanted particles entering turbine are common cause for corroded turbine blades. It is clear from fig 8. that the crack originates from the site of noticeable carbide presence, leading to crack propagation and ultimately fracture [29]. Corrosion combined with high temperature environment becomes *hot corrosion* and is defined as the accelerated corrosion due to presences of salts such as Na_2SO_4, NaCl, and V_2O_5, which combine to produce molten deposits that damage the protective oxide layer on surface. Sodium sulphate is a well-known corroding agent produced during combustion process. Sodium chloride may enter the combustion chamber and Sulphur is a constituent of almost all fuels [28].

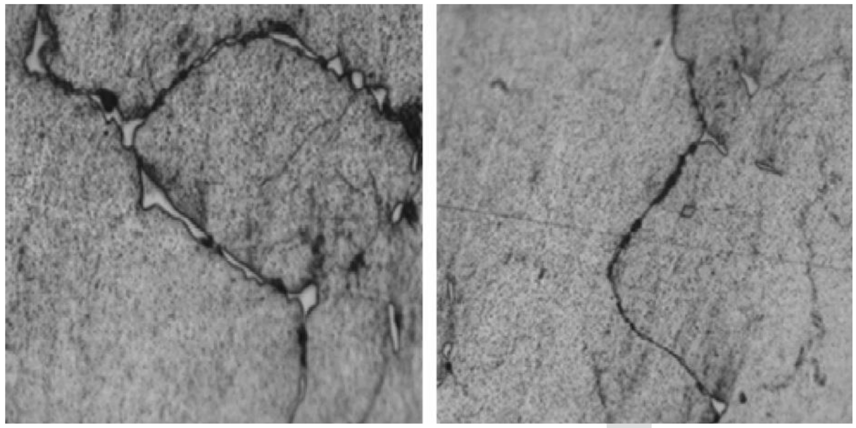

Fig 8. Continuous films of carbides in grain boundaries in two different zones
(Failure analysis of gas turbine blades in a thermal power plant, N. Vardar, A. Ekerim, Engineering Failure Analysis 14 (2007) 743–749)

3.5.1 Hot corrosion type 1

Extreme and rapid oxidation that occurs in presence of sodium sulphate and temperature range of 815 to 926 degree Celsius is known as *hot corrosion*. Main feature of this type of corrosion is that the base metal denuded surface experience an *intergranular* attack by sulphate particles as they are converted into complex unstable metal oxides. Similar behaviour is shown by potassium sulphate [28].

3.5.2 Hot corrosion type 2

This type of hot corrosion requires specific condition to attack at the most vulnerable site. Temperature between 593 to 760 degree Celsius and significantly pressurised SO_3 are the most favorable conditions along with the low melting constituents of nickel alloy like $NiSO_4$ and Na_2SO_4 that provide the need sulphate and oxygen compounds.

4. COOLING TECHNIQUE

First stage of any turbine encounters the highest temperature. In a gas turbine, blade tips are the most heated section of the entire blade. Cooling of components would protect them against overheating for safe operation as it would ensure limited thermal stresses which are experienced by the blades. This would result in proper cycle efficiency and enhanced component operational period. Steam turbine use cold steam as coolant, which is passed through the gaps between components. Gas turbine used film cooling technique for the purpose of blade cooling [24].

4.1 Film cooling

Film cooling works by injecting cool air through downwards inclined hole (fig 9.) in the boundary layer which covers the blade skin. This develops a cool film over the blade. Different hole patterns are used in modern film cooling to cover a full section of blade. This is known as full-coverage film cooling technique [25]. Study regarding the effects of tip clearance and blowing ratio on film cooling effectiveness, carried out by Kwah and Han [26] concluded that increase in effectiveness is directly proportional to both of the mentioned quantities. Factors influencing the film cooling performance are flow unsteadiness, compressibility, free stream turbulence, angle of ejection, three-dimensional external flow structure, hole size, location and shape, and wall curvature. Two dimensional injection model was developed by Tafti and Yavuzkurt that used two-dimensional Low-Reynolds number K-ε model boundary layer code for film cooling.

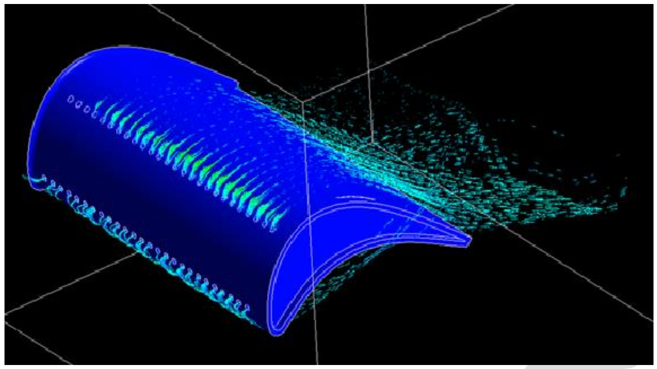

Fig 9. Film cooling in turbine blade
(http://cfd2012.com/ansys-cfx-turbine-cooling.html)

In two dimensional boundary layer full-coverage film cooling, the prediction of heat transfer is done by using Crawford's model. It was used for augmentation of eddy viscosity on flat surface. Though applicable only for flat surface, this is the excepted model for present day calculations as no better model is available. Eddy diffusivity for momentum in presence of film cooling is determined by augmenting Prandtl mixing length using the following relation [27]:

$$\frac{l}{\delta} = (\frac{l}{\delta})_{3D} + (\frac{l}{\delta})_{a} \quad (2)$$

Here '3D' refers to three dimensional mixing and 'a' refers to departure due to jet-boundary layer interaction given by:

$$\left(\frac{l}{\delta}\right)_a = \lambda_{max,a} * F * f \,, \quad (3)$$

$$F = 2.718 \left(\frac{y}{PD}\right)^2 \exp\left[-\left(\frac{y}{PD}\right)^2\right], \quad (4)$$

$$f = \exp\left[-\frac{\frac{x}{\delta}}{2}\right], \quad (5)$$

$$\lambda_{max,a} = 0.0353 \exp(2.65 B_r) \quad (6)$$

$$\lambda_{max,a} = 0.0177 \exp(2.64 B_r) \quad (7)$$

$$\lambda_{max,a} = 0.0601 \exp(3.46 B_r) \quad (8)$$

Equation (6), (7) and (8) are for slant angled injection, compound angled injection and normal injection respectively [27].

4.2 THERMAL BARRIER COATING

Thermal barrier coating (TBC) is another method to provide thermal protection to gas turbine blades from high temperature gases. TBC is made up of low-thermal conductive ceramic material. Surface temperature reduction of underlying super-alloy is observed when used in thickness range of 100 to 500µm. TBC is made up of four structural layers, two ceramic layer and two metallic layers, namely, the substrate layer, the bond coating, the thermally grown oxide layer and the ceramic top coat layer. Due to the complexity of these layers, simultaneous occurring of phenomenon like plastic deformation, thermal expansion, phase transformation, diffusion, oxidation, elastic deformation, thermal conduction, radiation, fatigue and fracture can be seen.

The multi-material nature of TBC makes it more complex than any other coating and helps the material to withstand extremely high temperature cycling and stress conditions. With the use of TBC, materials used are expected to operate for about 30,000 hours in industrial gas turbines and last thousands of take-off and landing cycles in commercial jet engines [30].

5. CONCLUSION

From the above study it can be concluded that the metallurgical and mechanical causes of blade failure will always be present. It is observed that extremely high temperature of gases flowing in turbine contributes a lot in blade degradation and to lessen the chances of failure, thermal protection of gas turbine components is of most importance. Advanced thermal protection for blades and components exposed to these extremely hot gases are the main area of research. Thermal stresses are concentrated on particular sections of blade due to the fact that the sites for hot gases to escape are the most vulnerable points for attack of hot corrosion and other damaging factors in whole turbine. Concept of thermal barrier coating is also a good area for research as it has great potential for future advancements. Film cooling is being used for turbine and rocket components. Talking about the metallurgical aspect, new materials with high temperature resistant properties along with resistance to failure at high load and mechanical stress are being developed. Advance manufacturing techniques are adopted to develop new generation super-alloys. The studies conducted by different researchers and the models developed which show the significant dependency of heat transfer rate through the blade surfaces should be used to full extent. This along with other researches should be tested and implemented to reduce the chances and causes of turbine blade failure which would ultimately lead to more efficient and less hazardous turbomachines.

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