

Failure analysis of gas turbine blades in a gas turbine engine used for marine applications

V. Naga Bhushana Rao^{1*}, I. N. Niranjan Kumar², K. Bala Prasad³

^{1*} Department of Marine Engineering, Andhra University College of Engineering, Visakhapatnam, INDIA

² Department of Marine Engineering, Andhra University College of Engineering, Visakhapatnam, INDIA

³ Department of Marine Engineering, Andhra University College of Engineering, Visakhapatnam, INDIA

*Corresponding Author: e-mail: vnbrao24ster@gmail.com Tel +91-8985003487

Abstract

High pressure temperature (HPT) turbine blade is the most important component of the gas turbine and failures in this turbine blade can have dramatic effect on the safety and performance of the gas turbine engine. This paper presents the failure analysis made on HPT turbine blades of 100 MW gas turbine used in marine applications. The gas turbine blade was made of Nickel based super alloys and was manufactured by investment casting method. The gas turbine blade under examination was operated at elevated temperatures in corrosive environmental attack such as oxidation, hot corrosion and sulphidation etc. The investigation on gas turbine blade included the activities like visual inspection, determination of material composition, microscopic examination and metallurgical analysis. Metallurgical examination reveals that there was no micro-structural damage due to blade operation at elevated temperatures. It indicates that the gas turbine was operated within the designed temperature conditions. It was observed that the blade might have suffered both corrosion (including HTHC & LTHC) and erosion. LTHC was prominent at the root of the blade while the regions near the tip of the blade were affected by the HTHC. It could be concluded that the turbine blade failure might be caused by multiple failure mechanisms such as hot corrosion, erosion and fatigue. Hot corrosion could have reduced the thickness of the blade material and thus weakened the blade. This reduction of the blade thickness decreases the fatigue strength which ultimately led to the failure of the turbine blade.

Keywords: Failure analysis, Turbine blade failure, Superalloy, Hot corrosion, Sulphidation, Metallurgical examination.

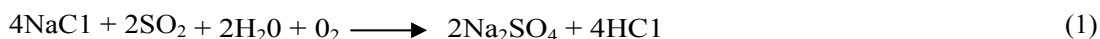
DOI: <http://dx.doi.org/10.4314/ijest.v6i1.5>

1. Introduction

Whether propelling aircraft through the sky, ships through the ocean or providing power to the electrical grid, gas turbine engines have become incorporated into our daily lives. As world moves towards a higher dependence on technology, there will be an increased demand for gas turbine engines to produce power with higher efficiencies. The purpose of gas turbine technology is to extract the maximum of energy from the high temperature high pressure gases and the Turbine is responsible for extracting energy from the high temperature, high pressure gas produced by the combustor. The turbine blades of a gas turbine were considered as the critical components of the gas turbine engines in which failures occur frequently. In some studies, it was reported that as many as 42 percent of the failure in gas turbine engines were only due to blading problems and thus the turbine blades are often the limiting component of gas turbines. The gas turbine blades principally made of Nickel-based superalloy. The excellent thermal stability, tensile and fatigue strengths, resistance to creep and hot corrosion, and micro-structural stability possessed by nickel-based superalloy render the material an optimum choice for application in turbine blades (Sims, 1999; Boyce, 2002; Huda, 2007). These Nickel based superalloy are the standard material for hot stages of gas turbines, where blades are subjected to high mechanical stresses, elevated temperatures and in aggressive environments (Ray, 2000; Ray and Steinbrech, 1999; Brindley and

Miller; 1990; Liebert and Miller, 1984; Kokini et al., 1997; Lelait et al., 1989; Kokini and Takeuchi, 1994; Godiwalla et al., 2001; Roy et al., 2001, 2006; Chiu and case, 1991; Owen and Hinton, 1980; Brandle et al., 1996; Roy et al., 2004; Gupta et al., 1996).

Hot section blades typically fail because of creep, fatigue including both low cycle fatigue (LCF) and high cycle fatigue (HCF), oxidation, erosion and foreign object damage (Mazur, 1999). Contributing factors often include environmental attack, sulphidation, corrosion, cyclic loads etc. Gas turbine engines have been successfully operated in wide range of fuels including heavy fuels and these fuels may contain corrosive elements like sulfur, sodium, potassium, vanadium, lead, molybdenum etc as contaminants. The turbines blades of gas turbine engines operated at elevated temperatures in this type corrosive environment, causes serious hot corrosion problems. Fuel contamination with salt water is exceedingly common when fuel transported by barges. Salt can enter the gas turbine engines by means of air and this problem is serious in gas turbine engines especially those used in marine applications. The contaminants in the fuel and air may lead to deposition of alkali metal sulfates on the surface of the blade and resulting in the hot corrosion attack (McMinn, 1987). Hot corrosion is an accelerated damage phenomenon that occurs when high temperature turbine blades made of super alloys are operated in an environment containing salt and sulfur. The salt is derived from the air or enters the turbine via the fuel. Sulfur typically enters the turbine via the fuel. The basic reaction that occurs is represented by:



Hot corrosion on turbine blades can be intensified by the presence of vanadium, which produces V_2O_5 , in combination with the alkalis, while in molten state, can aggressively dissolve metal oxides. High temperature hot corrosion is also known as Type I corrosion, which occurs in the approximate temperature range of 825°C to 950°C (Meher-Homji). Figure.1 shows the micro-structure of the surface of the turbine blade material near the tip which has suffered from the hot corrosion.

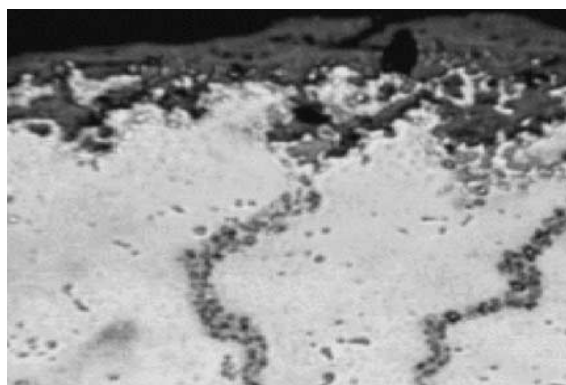


Figure 1. Type I hot corrosion, grain boundary diffusion

Low temperature hot corrosion (LTHC) is also known as Type II hot corrosion which occurs during the approximate temperature range of 700°C to 800°C . From the Figure.2, it was noticed that the pitting attack was typically non-uniform, with layered type corrosion scales. No intergranular attack was found in the base metal. Very little sulphide formation within the metal was observed. Figure.2 shows the micro-structure of the surface of the blade material close to the root of the blade with no grain diffusion but suffered from low temperature hot corrosion (LTHC). In both types of hot corrosion, there is a breakdown in the protective oxide layer scale aided by thermal cycling (Meher-Homji).

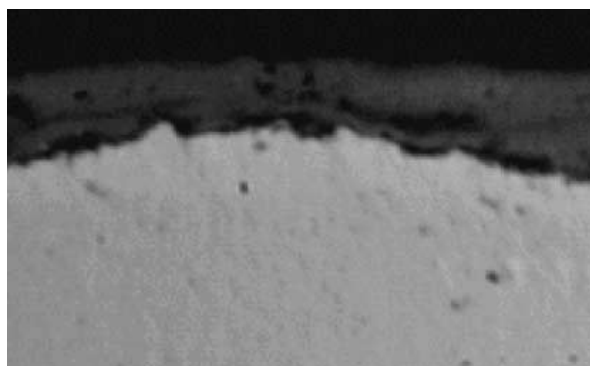


Figure 2. Type II hot corrosion, no grain boundary diffusion

To investigate the causes of high pressure temperature (HPT) turbine blade failures, the turbine blade of 100 MW gas turbine engine intended for operation onboard ship using fuel as LSHF HSD (Low Smoke Halogen Free High Speed Diesel) was

considered for the experimentation. Before failure, this gas turbine blade was operated for about 10000 hours while its service life was expected to be around 15000 hours. According to design, it was expected that if gas turbine engine has been operated as per designed working conditions, the turbine blade could have an expected service life of 15000 hours. Generally, the failure analysis of gas turbine blades can be carried out in the following two ways to predict the mode of failure.

- Metallurgical analysis and
- Mechanical analysis

In this paper, an attempt has been made to analyze the failure of gas turbine blade made of Nickel base super alloy through metallurgical examination. This metallurgical examination was carried out assuming that there might be some micro-structural changes in the blade material due to blade operation at elevated temperature which led to the ultimate failure of the gas turbine blade.

The experimental procedure consists of visual inspection, determination of material composition, microscopic examination and metallurgical analysis. Specimens were collected from different regions of the blade to carry out the metallurgical examination. The aim of this investigation is to identify the main causes of the HPT turbine blade failures and to suggest the necessary measures to be taken to avoid similar failures in future. This may help to operate the gas turbine blade used in gas turbine engine for marine applications upto its expected service life.

2. Background data

It was reported that the blades under investigation, belonging to a 100 MW gas turbine engines used for marine application with a turbine gas inlet temperature of around 950⁰C. The turbine blade was made of Nickel-Base super alloys and was manufactured by investment casting method. The composition of HPT turbine blade is shown in table.1. It was observed that the blade was badly damaged at the time of removal.

Table 1. Chemical composition of HPT turbine blade made of Nickel based superalloy

Element	C	S	P	Mn	Si	Cr	Ni	Mo	Ti	W	Fe	Al	Co
wt%	0.009	0.004	0.004	0.01	0.12	19	67.81	6.10	1.56	3.05	0.48	1.73	0.067

3. Experimental Procedure

The failed HPT gas turbine blade was presented in figure 3. The blade that had operated for about 10000 hrs before its failure was made of Ni-based superalloy. The failed blade considered here was used in gas turbine engines meant for marine applications. As a part of investigation on the gas turbine blade, the following activities have been carried out to know the causes of blade failures.

- Macroscopic inspection,
- Material verification,
- Microscopic examination through optical microscopy and
- Metallurgical analysis.

For these procedures, some specimens were prepared from the failed blade. Specimens for micro-structure analysis were collected from three different regions of the failed blade - one from the root, one from the mid span and other from the tip of the blade material. These specimens were polished by standard metallographic procedures and then etched by a suitable solution of Glyceregia.



Figure 3: HPT Gas turbine blade

4. Results and Discussions

4.1. Quantitative Examination of blade material

From the results of spectro chemical test of the blade material, it was found that the Turbine blade was made of Nickel-Based superalloy and has chemical composition as shown in table 1. The result revealed that the blade composition also included the elements like Sulfur (S), Silicon (Si) etc. It was observed that there were certain dark points distributed over the surface of the blade material, which are attributed to the presence of the elements like sulfur and silicon (Gallardo, 2002).

4.2 Macroscopic Inspection of a turbine blade

The macroscopic features of the turbine blade were observed by visual examination as a part of failure analysis. Very rough surface was noticed in the region, close to the root of the blade, and exhibited some colour change shown in Figure 4. (a). This indicates the formation of low temperature hot corrosion at this region of the blade. At the region close to the root of the blade, the temperature is normally lower than the temperature of the other parts of turbine blade during operation and therefore, these regions could be prone to be affected by low temperature hot corrosion (LTHC). Previous researchers have confirmed from their studies that the low temperature hot corrosion (LTHC) was more affective in the region close to the root of the blade and with increasing height from the root (platform), the extent of this type of corrosion gradually decreased (Viswanathan, 2001).

From the Figure 4 (b) it was observed that there was loss of some material and thickness as well, at the tip of the turbine blade which is attributed to the combined mechanisms such as hot corrosion and fatigue etc. It was further observed that there was a presence of green coloration at the tip of the blade. Some studies have reported that the greenish colour is a macroscopic feature of high temperature hot corrosion (HTHC) (Eliaz, 2002). In another study, it was confirmed that HTHC occurs away from the edges and with increasing height from the base (root) of the blade, the extent of this type of corrosion increased (Viswanathan, 2001).

Based on the visual observation and material verification, it was concluded that there was a formation of sulphidation on the turbine blade surface. Sulphidation is an important contributing factor to the failure of turbine blades especially in the turbines operating in marine environment. Figure .4 (c) depicts the pressure side of the blade which shows the damage due to hot corrosion. It was more severe near the trailing edge. The sulfur from the fuel might have reacted with the protective oxide layer attacking the base impurities, resulted in the formation of slag called liquid sodium sulfate (Na_2SO_4). Under this slag, protective oxide layer might be broken down, permitting the attack of parent blade material and causing very severe damage. This mechanism of sulphidation will rapidly damage the base material and results in loss of material. The loss of material could shift natural frequencies into dangerous regions causing the blade to vibrate with much higher amplitudes (resonance) and thereby leading to high cycle fatigue and reduced blade life time (Cyrus).



Figure 4 (a). Rough surface of the blade at the root, (b). Surface of the blade near its tip which shows some green coloration, (c). Pressure side of the blade showing the damage due to hot corrosion

4.3. Micro-structural evaluation of turbine blade material

The gas turbine blades are to be operated at elevated temperature to have an advantage of having higher efficiency and higher work output. Thus the elevated temperature might be the cause for the failure of the turbine blade. To analyze the cause and mode of failure mechanism of the damaged blade, micro-structural examination of the blade was made at three different zones of the blade. The micro-structure of the blade material was carried out at the root of a blade, in the mid span (airfoil region) and at the tip of the blade. The root of the blade was not exposed to hot combustible gases i.e. subjected to lowest temperatures and hence the micro-structural changes are not very significant. Because of these lowest temperatures at the root of the blade, it was considered as the reference zone for micro-structural analysis. The micro-structure at the root of the blade material was compared to the micro-structure of the blade at other two zones i.e. mid-span and tip of the blade.

It was observed that the micro-structure at the root of the blade consisting of equiaxed grains of nickel solid solution with grain size of approximately 3-4. Fine particle of γ' precipitated within the matrix and dispersed carbide particle were found in the grain

boundaries. This type of micro-structure is common for γ^1 precipitated Nickel-Based super alloys. Although the root of the blade was considered as cold zone which normally does not suffer considerable changes in its micro-structure, but it may sometimes possible to observe some slight elongation of the original shape of γ^1 . This type of micro-structure indicates that the root material of the blade was not exposed to high temperature. A similar micro-structure was found at the mid span (air foil) region of the blade material, which indicates that this part of the blade material was also not subjected to overheating i.e. this is the region, normally subjected to the highest temperature of the blade but in this application, the temperatures might be controlled and were within the permissible limit of temperature and micro-structure was not affected by blade operation at higher temperature. Samples for micro-structural evaluation were also taken from the tip of the blade material. The micro-structure shows the carbides and gamma prime phases. In this carbides were decorating the grain boundaries. This micro-structure was almost similar to that of root and mid span of the blade. This means that there was no evidence of micro-structural damage noticed due to operation of a blade at elevated temperatures. These results show that the turbine blades of gas turbine engines used for marine applications were operated in normal operating temperature conditions. From these results it was understood that, there was no failure noticed in the gas turbine blade under examination due to blade operation at high temperatures which might be within the limits.

5. Conclusion

The failure analysis was carried out on a 100 MW gas turbine engine used for marine applications. Its blades were made of Nickel based superalloy to sustain high temperature conditions and other corrosive environmental conditions. The micro-structural evaluation of the blade material at three different regions (root, midspan and tip) of the blade revealed that there was no micro-structural damage took place due to operation of the blades at elevated temperatures, indicating that the turbine blades were operated in designed/normal operating temperature conditions. The turbine blades might have suffered due to both HTHC corrosion and LTHC corrosion apart from erosion. It was noticed that at the root of the blade, the surface was very rough and exhibited some colour change. It indicates the occurrence of the low temperature hot corrosion (LTHC) at this region of the blade.

At the tip of the turbine blade, it was observed that there was loss of some material and reduction in thickness. This indicates that the blade tip might have been subjected to the combined mechanisms such as hot corrosion and fatigue. Some green coloration was also noticed at the tip of the turbine blade. It is a clear indication of the occurrence of high temperature hot corrosion (HTHC). Also observed number of rubbing and scrubbing marks on the pressure side surface of the blade. It was further noticed that the turbine blades were subjected to erosion by some particulate matter. The source of this particulate matter might be from the compressor casing during the compression process or protective coating materials used in the combustor. Finally, it was concluded that the turbine blade failure of gas turbine used for marine application was caused by multiple failure mechanisms such hot corrosion, erosion and fatigue. The hot corrosion reduced the thickness of the blade material and thus weakened the blade. This reduction of blade thickness decreased the fatigue strength of the blade which finally led to the failure of the turbine blade.

References

- Boyce M.P. 2002. Materials: The gas turbine engineering handbook. 2nd edition, Houston, Texas: Gulf Professional Publishing, pp. 411.
- Brindley W.J. and Miller R.A., 1990. Thermal barrier coating life and isothermal oxidation of low-pressure plasma-sprayed bond coat alloys, *Surface Coating Technology*, Vol. 43/44, pp. 446-457.
- Brandle W.J., Grabke H.J., Toma D., and Krueger J.J., 1996. The oxidation behavior of sparyed MCrAlY coatings, *Surface Coating Technology*, Vol. 86/87, No. 1, pp. 41-47.
- Chin-Chen Chiu and Eldon D. Case, "Elastic modulus determination of coating layer as applied to layered ceramic composites: *Material Science Engineering: A* 132, 1991, pp. 39-47.
- Eliaz N, Shemesh G, Latanision R.M. 2002. Hot corrosion in gas turbine components. *Engineering Failure Analysis*, Vol. 9, p. 31
- Gallardo JM, Rodriguez JA, Herrera EJ. 2002. Failure of gas turbine blades. *Wear*, Vol. 252, pp. 258-264.
- Godiwalla K.M, Roy N., Chaudhuri S. and Ray A.K, 2001. Investigation and modelling of mechanical properties for thermal barrier coatings in gas turbine vane specimens under bending, *International Journal of Turbo and Jet Engines*, Vol. 18, No. 2, pp. 77-103.
- Gupta B., Gopalkrishnan B., Yadhav J., and Saha B., 1996. *Aerospace Materials with General Metallurgy for Engineers*, Vol. 2, , Aeronautical Research and Development Board, S. Chand and Company Ltd.: New Delhi, India.
- Huda Z. 2007. Development of heat-treatment process for a P/M superalloy for turbine blades. *Mater Des*, Vol. 28, No. 5, pp. 1664-1667.
- Kokini K., Choules C.D., and Takeuchi, Y.R., 1997. Thermal fracture mechanisms in ceramic thermal barrier coatings", *Journal of Thermal Spray Technology, JTTEE5, ASM International*, Vol. 6, No. 1, pp. 43-49.
- Kokini K. and Takeuchi, Y.R., 1994. Initiation of surface cracks in multilayer ceramic thermal barrier coatings under thermal loads" *Materials Science and Engineering: A*, Vol. 189, No. 1-2, pp. 301-309.
- Lelait L., Alperine Diot S.C., and Mevrel M., 1989. Thermal barrier coatings: Micro-structural investigation after annealing " *Materials Science and Engineering: A*, Vol. 121, pp. 475-482.
- Liebert C.H. and Miller R.A., 1984. Ceramic thermal barrier coatings, *Ind. Eng. Chem. Prod. Res. Dev.*, pp. 334-349.

- Mazur Z., González R. G., Kubiak J..1999. Técnicas de Reparación y Extensión de la Vida de los Álabes de Turbina de Gas; Instituto de Investigaciones Eléctricas, Cuernavaca, pp. 25-42.
- McMinn A. 1987. Coatings technology for hot components of industrial combustion turbines: a review of the state of the art. Research Project 2388-3. Electric Power Research Institute.
- Meher-Homji C.B., Gabriles G., Gas turbine blade failures: Causes, avoidance, and troubleshooting, Proceedings of the 27th turbomachinery symposium, Turbo machinery laboratory, Texas, A&M university, pp. 129-180.
- Owen D.R.J. and Hinton E., 1980. *Finite Element in Plasticity*, Pineridge Press Limited: Swansea, UK.
- Ray A.K., 2000. Failure mode of thermal barrier coatings for gas turbine blade under bending, *International Journal of Turbo and Jet Engines*, Vol. 17, pp. 1-24.
- Ray A.K. and Steinbrech R.W., 1999. Crack propagation studies of thermal barrier coatings under bending, *Journal of European Ceramic Society.*, Vol. 19, No. 12, pp. 2097-2109.
- Roy N., Godiwalla K.M., Chaudhuri S. and, Ray A.K., 2001. Simulation of bond coat properties in thermal barrier coatings during bending, *High Temperature Materials and Processes*, Vol. 20, No. 2, pp. 103-116.
- Roy N., Godiwalla K.M., Dwarakadasa E.S., Ray A.K., 2004. Elasto-plastic deformation in thermal barrier coated superalloys, *Scripta Meterialia*, Vol. 51, No. 7, pp. 739-743.
- Ray A.K., Singh S.R., Swaminathan, J., Roy P.K., Tiwari Y.N., Bose S.C., and Ghosh R.N., 2006, Structure property correlation study of a service exposed first stage turbine blade in a thermal power plant, *Materials Science and Engineering*, A 419, pp. 225–232.
- Viswanathan R. 2001. An investigation of blade failures in combustion turbines. *Engineering Failure Analysis*, Vol. 9, pp. 493.
- Sims CT. 1999. Non metallic Materials for gas turbine engines:are they real?, *Advanced Material Processes*, Vol. Vol. 139, No. 6, pp. 32-39.

Biographical notes

V. Naga Bhushana Rao is with the Department of Marine Engineering, Andhra University College of Engineering, Visakhapatnam, India.

I. N. Niranjan Kumar is with the Department of Marine Engineering, Andhra University College of Engineering, Visakhapatnam, India.

K. Bala Prasad is with the Department of Marine Engineering, Andhra University College of Engineering, Visakhapatnam, India.

Received February 2013

Accepted August 2013

Final acceptance in revised form October 2013