International Journal of Advanced Science and Technology
Vol.68 (2014), pp.57-64
http://dx.doi.org/10.14257/ijast.2014.68.06

Mechanical Analysis of 1st Stage Marine Gas Turbine Blade

V. NagaBhushana Rao[1], I. N. Niranjan Kumar[2], N. Madhulata[3] and A. Abhijeet[4]

[1]*(Department of Marine Engineering, Andhra University College of Engineering, India)*
[2]*(Department of Marine Engineering, Andhra University College of Engineering, India)*
[3]*(Department of Marine Engineering, PRIME Engineering College, Visakhapatnam, India)*
[4]*(Department of Mechanical Engineering, Raghu Institute of Technology, Visakhapatnam, India)*
[1]*Corresponding Author: e-mail: vnbrao24ster@gmail.com Tel +91-8985003487*

Abstract

Turbine blades of a gas turbine are responsible for extracting energy from the high temperature, high pressure gases. These blades are operated at elevated temperatures in aggressive environments and are subjected to large centrifugal forces. As many as 42 percent of the failures in gas turbine engines were only due to blading problems and the failures in these turbine blades can have dramatic effect on the safety and performance of the gas turbine engine. In this research paper, an attempt has been made to analyze the failure of gas turbine blade through Mechanical analysis. The blade under investigation belongs to a 30 MW gas turbine engines used in marine applications and is made of Nickel-Base superalloys. Before failure, the turbine blade was operated for about 10000 hours while its service life was expected to be around 15000 hours. Mechanical analysis has been carried out assuming that there might be failure in the blade material due to blade operation at elevated temperature and subjected to large centrifugal forces. The gas turbine blade model profile is generated by using CATIA V5R21software. The turbine blade is analyzed for its thermal as well as structural performance. It was observed that there was no evidence of rubbing marks on the tip section of turbine blade indicating the elongation of the blade is within the safe limit. Maximum stresses and strains are observed near to the root of the turbine blade and upper surface along the blade roots. Maximum temperatures are observed at the blade tip sections and minimum temperature at the root of the blade. Temperature distribution is decreasing from the tip to the root of the blade section. The temperatures observed are below the melting temperature of blade material.

Keywords: *Marine gas turbine blade, failure analysis, modeling, structural analysis, thermal analysis*

1. Introduction

The purpose of gas turbine technology is to extract the maximum energy from the high temperature high pressure gases produced by combustor. This could be achieved by improving the thermal efficiency of the gas turbine engine. Attempts were being made to increase the power output and thermal efficiency of a gas turbine engine by operating turbine at elevated temperatures as it is understood that the efficiency of gas turbine is a direct function of turbine inlet temperature (TIT) [1].

Turbine blades are the individual components which make up the turbine section of a gas turbine engine and are responsible for extracting energy from the high temperature,

ISSN: 2005-4238 IJAST

high pressure gases produced by the combustor. The turbine blades are often the limiting component and were considered as the critical components of the gas turbine engines in which failures occur frequently [2].

During service, high pressure turbine (HPT) blades undergo various types of time-dependent degradation due to exposure in the operating environment and are considered as the most important rotational components of gas turbine engine. These turbine blades are subjected to high mechanical stresses, elevated temperatures and are operated in aggressive environments [3-17]. To survive in this difficult environment, turbine blades often made from exotic materials like superalloys. Superalloys are metallic materials for service at high temperatures, particularly in the hot zones of gas turbines. Superalloy materials allow the turbine to operate more efficiently by withstanding higher temperatures. Super alloys were developed since the second quarter of the 20th century as materials for elevated temperature applications and can be divided into three groups: nickel-base super alloys, cobalt-base super alloys and iron base super alloys. The gas turbine blades principally made of Nickel-base superalloys. The excellent thermal stability, tensile and fatigue strengths, resistance to creep and hot corrosion, and micro structural stability possessed by Nickel-base superalloys render the material an optimum choice for application in turbine blades [18-20]. Failures in this turbine blade can have dramatic effect on the safety and performance of the gas turbine engine. In some studies, it was reported that as many as 42 percent of the failures in gas turbine engines were only due to blading problems. In this regard, investigation has been made to know the cause of turbine blade failures and thus to improve the service life of turbine blades.

In this paper an attempt has been made to investigate the causes of high pressure temperature (HPT) turbine blade failures. The turbine blade under evaluation belonging to 30 MW gas turbine engine intended for operation onboard ship using fuel as LSHF HSD (Low Smoke Halogen Free High Speed Diesel). 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 been operated in 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

Previously some work had been carried out on failure of turbine blade through metallurgical examination which includes the activities such as determination of material composition, visual inspection and micro-scopic 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 a gas turbine blade [21].

In this research paper, an attempt has been made to analyze the failure of gas turbine blade made of Nickel base superalloys through Mechanical analysis. Mechanical analysis has been carried out assuming that there might be failure in the blade material due to blade operation at elevated temperature and subjected to large centrifugal forces which finally led to the ultimate failure a gas turbine blade.

This research work mainly focuses on structural and thermal analysis turbine blade using ANSYS 14.0. Reverse Engineering is adopted to generate 3D surface data of turbine blade under analysis. The data to make real model of a turbine blade is obtained using Coordinate Measuring Machine (CMM). The gas turbine blade model profile is generated by using CATIA V5R21software. 3D model of a gas turbine blade with root was done in two stages. These two were then combined to make a single volume using union Boolean operation. The turbine blade is analyzed for its thermal as well as structural performance. Static analysis was carried out to know the mechanical stresses and elongation experienced by the gas turbine rotor blades, which includes the parameters such as the gas forces which are assumed to be distributed evenly, the tangential and axial forces act through the centroid of the blade. The centrifugal force also acts through the centroid of the blade in the radial direction. Thermal analysis was carried out to know the thermal stresses and the temperature distribution by applying temperatures and thermal fluxes of the gas turbine rotor blades.

2. Back Ground Data

It was reported that the blades under investigation, belonging to a 30 MW gas turbine engines used for marine application with a turbine gas inlet temperature of around 950^{0}C. The turbine blades were made of Nickel-Base super alloys and were manufactured by investment casting method. The composition of HPT turbine blade is determined using spectro-chemical test and is shown in Table 1. The turbine blade under evaluation is shown in Figure 1. It was observed that the turbine blade was damaged during periodic service.

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

Figure 1. High Pressure Temperature (HPT) 1st Stage Gas Turbine Blade

3. Modeling of Gas Turbine Blade

The blade under examination belonging to 1st stage turbine blades of 30 MW gas turbine engine intended for operation onboard ship. Reverse Engineering (RE) is being applied to generate 3D surface data of turbine blade of a gas turbines engine meant for marine applications. The gas turbine blade model profile is generated by using CATIA V5R21software. 3D model of a gas turbine blade with root was done in two stages. These two were then combined to make a single volume using union Boolean operation. Geometric model of gas turbine blade using CATIA V5 R21 is shown in Figure 2.

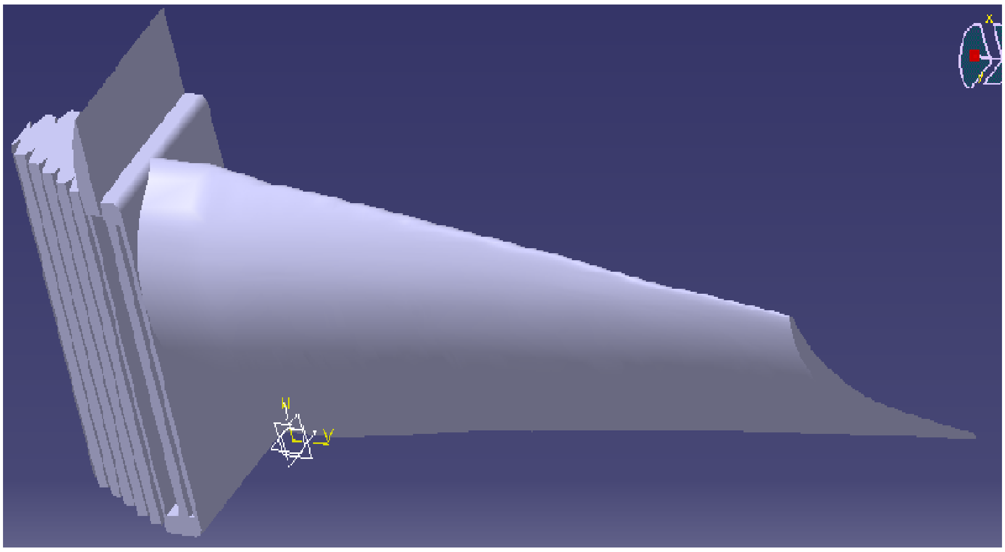

Figure 2. Geometric Model of Gas Turbine Blade Using CATIA V5 R21

4. Finite Element Method

The stress analysis in the field of gas turbine engineering is invariably complex and for many of the problems, it is extremely difficult and tedious to obtain analytical solutions. The finite element method is a numerical analysis technique for obtaining approximate solutions. It has now become a very important and powerful tool for numerical solution of wide range of engineering problems. The method being used for the analysis of structures solids of complex shapes and complicated boundary conditions. The advance in computer technology and high-speed electronic computers enables complex problems to model easily. Various researches have done lot of work to develop analysis of gas turbine rotor blade using finite element analysis.

5. Finite Element Analysis of a Gas Turbine Blade

The turbine blade is analyzed for its thermal and structural performance. The structural and thermal analysis of a gas turbine is carried out using ANSYS 14.0 software. Single blade is taken into consideration for analysis as turbine blades are mounted on the periphery of hub symmetrically along the axis of rotation of the blade. The cross section of the blade is in the X-Y plane and the length of the blade is along the Z axis. Centrifugal forces generated during service by rotation of the disc were calculated by applying an angular velocity to the turbine blade. A gas pressure was also applied over the aerofoil. The temperatures of the blade and disc were non-uniform, inducing thermal stresses by differential thermal expansion.

Static analysis was carried out to determine the mechanical stresses, strains and elongation experienced by the gas turbine rotor blade. In this analysis, the gas forces are assumed to be distributed evenly, the tangential and axial forces act through the centroid of the blade. The centrifugal force also acts through the centroid of the blade in the radial direction.

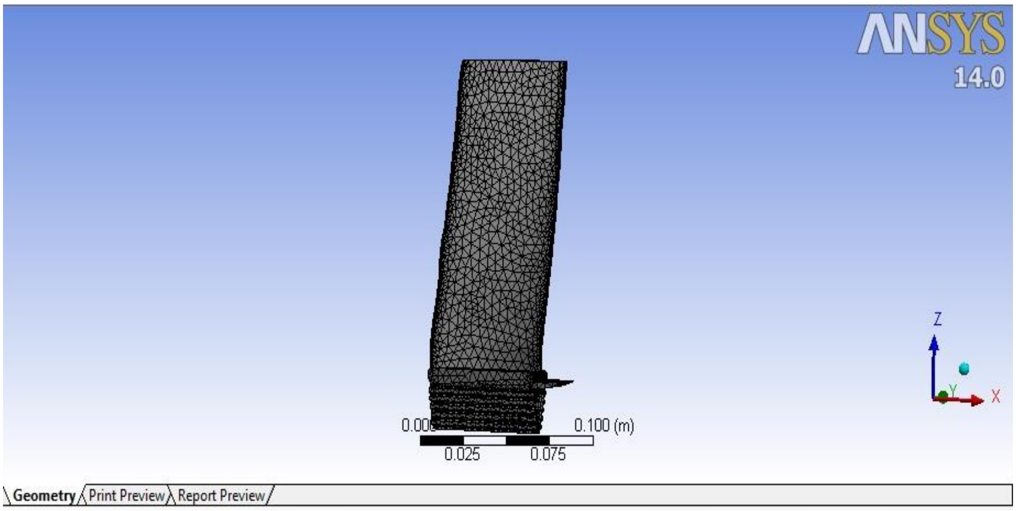

Figure 3. Meshing of Turbine Blade Under Analysis

Tangential forces (Ft) = 980 N
Axial force (Fa) = 250 N
Centrifugal force (Fc) = 282661.8 N

Thermal analysis was carried out to determine the thermal stresses such as the temperature distribution of the gas turbine rotor blade. Thermal analysis plays an important role in the designing and analyzing the failure in the gas turbine blade materials operated at elevated temperatures.

6. Results and Discussions

Blade failures can be caused by a number of mechanisms under the turbine operating conditions of high rotational speed at elevated temperature in corrosive environments. To identify the causes of the blade failures, a complete investigation has to be carried out, integrating both the metallurgical examination and mechanical analyses. This work focuses on failure analysis of gas turbine blades found in gas turbine engines meant for marine propulsion through mechanical analysis. This research work deals with the modeling and analysis of gas turbine blades. The thermal-structural finite element analysis was performed on the turbine blades using ANSYS 14.0 software and results were discussed. Exhaust gases from the combustor are directed through the turbine in such a manner that the hottest gases impinge on turbine blades, at or near their tips. So the tip of HPT first stage blade is normally the point of the highest temperature in the turbine portion. In order to extract the maximum amount of energy from the hot stream of exhaust gases, the clearance between the blade tips and the adjacent shrouds is kept at a minimum. However, as a result of dimensional tolerance during manufacturing operations and creep stretch of turbine blade during hot operations, in abnormal conditions, the tips of the airfoils can severely rub into the non-rotating shroud causing a ‘‘tip-rub’ [22].

The force of high temperature gases impinging on the turbine blade has two components: tangential force (Ft) and axial force (Fc). These gas forces are evaluated by constructing velocity triangles at inlet and outlet of the rotor blades. The Centrifugal, Axial and Tangential forces acting on the blade are considered as loads in structural analysis. The convective heat transfer coefficients were calculated using the heat transfer empirical relations taken from the heat transfer design dada book. After calculating the heat transfer coefficients and gas forces, the rotor blade was then analyzed using ANSYS 14.0. After completing the analysis of a turbine blade, the results are discussed. The maximum mechanical stresses and elongations and maximum temperature induced in the turbine blade materials are within the safe limit. Maximum elongations observed at the blade tip sections and minimum elongations at the root of the blade.

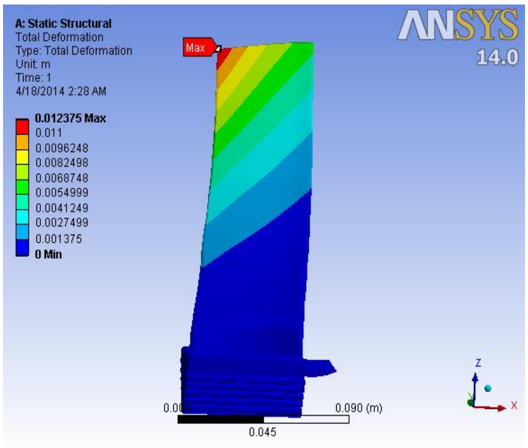

Figure 5.3 shows deformation produced in the turbine blade due to action of all forces such as gas and centrifugal forces. It is observed that the maximum deformation of 0.01237 m occurs at the tip section of turbine blade material and the minimum occurs at the root section. There was no evidence of rubbing between tip of the turbine blade and casing indicating elongation is within the limit.

Figure 5.1. Deformation of the Turbine Blade Due to Gas Pressure and Combined Loading

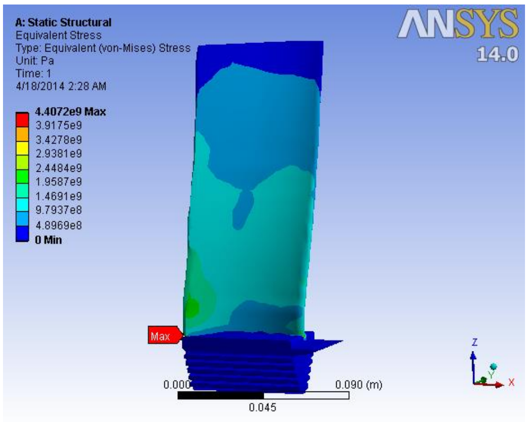

Figure 5.2 shows the stress distribution in the turbine blade due to action of all forces such as gas and centrifugal forces. It is observed that the maximum stress of 1.958 GPa occurs at the root section and on the pressure side of gas turbine blade. Minimum stress occurs at the tip section.

Figure 5.2. Stress Distribution in the Turbine Blade Due to Gas Pressure and Combined Loading

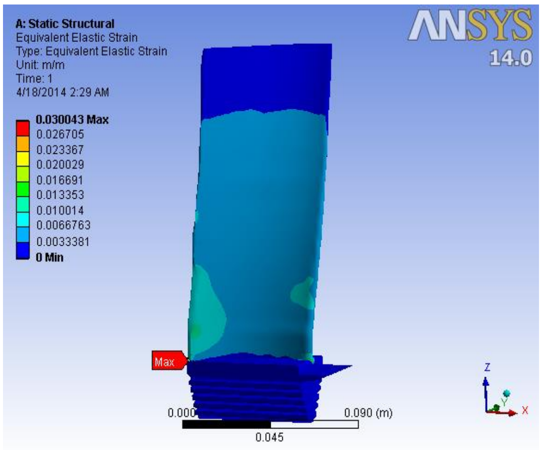

Figure 5.3 shows the Strain distribution in the turbine blade due to action of all forces such as gas and centrifugal forces. It is observed that the maximum stress of 0.013353 m/m occurs at the root section and on the pressure side of gas turbine blade. Minimum stress occurs at the tip section.

Figure 5.3. Strain Distribution in the Turbine Blade Due to Gas Pressure and Combined Loading

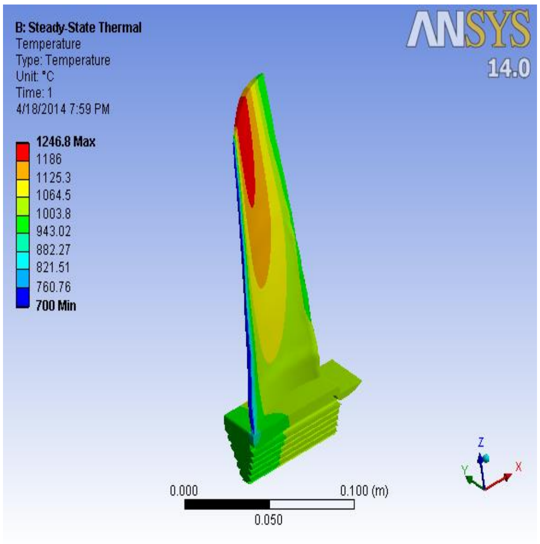

Figure 5.4 shows the Temperature distribution in the turbine blade made of superalloy due to temperature gradient and heat flux. It is observed that Maximum temperature of 1246.8 ^{0}C occurs at the tip section and minimum temperature occurs at the root of the turbine blade. This non uniform temperature at tip and root of the blade materials might induce the thermal stresses in the turbine blade.

Figure 5.4. Temperature Distribution in the Turbine Blade

7. Conclusions

The goal of the gas turbine technology is to extract maximum amount of energy from the gases at high temperature which could be achieved by improving the thermal efficiency of the gas turbine engine. The efficiency of gas turbine is a direct function of turbine inlet temperature (TIT) and operating the gas turbine blade at high temperature would provide better efficiency and maximum work output. The turbine blades are responsible for extracting energy from the high temperature, high pressure gas produced by the combustor. These turbine blades are operated at elevated temperatures in aggressive environments and subjected to large centrifugal forces. The thermal stress analysis together with the mechanical stress analysis will yield more valuable information about the actual magnitudes of the overall stresses encountered in turbine blades. In this research work, an attempt has been made to analyze causes for the failure of gas turbine blade made of Nickel base super alloy through Mechanical analysis. Mechanical analysis has been carried out assuming that there might be failure in the blade material due to blade operation at elevated temperature and action of large centrifugal forces which finally led to the ultimate failure a gas turbine blade. The work deals with the modeling and analysis of gas turbine blade. The thermal-structural finite element analysis was performed for the turbine blade using ANSYS 14.0. The results obtained were presented in the form of contour maps and profiles of temperature distributions, radial elongations and mechanical stresses for the rotor blades.

Maximum elongations observed at the blade tip sections and minimum elongations at the root of the blade. It was observed that there was no evidence of rubbing marks on the tip section of turbine blade indicating the elongation of the blade under evaluation is within the safe limit.

Maximum stresses and strains are observed near to the root of the turbine blade and upper surface along the blade roots. The maximum stress of 1.958 GPa occurs at the trailing edge nearer to the root of the blade exceeds the yield stress of the material and this might leads to the failure of the turbine blade. At all other parts of turbine blade, the stresses induced are within the same limits.

Maximum temperatures are observed at the blade tip sections and minimum temperature at the root of the blade. Temperature distribution is linearly decreasing from the tip of the blade to the root of the blade section. The temperatures observed are below the melting temperature of blade material. The temperature has a significant effect on the overall turbine blade. This non uniform temperature at tip and root of the blade materials might induce the thermal stresses in the turbine blade. These thermal stresses along with the mechanical stresses set up in the turbine blade might reduce the life of blade material. The results obtained in the present work add the information for the design of high pressure and temperature (HPT) turbine blades of multistage gas turbine of higher outputs and efficiencies.

References

[1] W. W. Bathie, "Fundamentals of gas turbines", John Wiley and Sons, New York, **(1996)**.
[2] M. P. Boyce, "The gas turbine handbook", 2nd ed. Houston, Texas: Gulf Professional Publishing, **(2002)**, pp. 368.
[3] A. K. Ray, "Failure mode of thermal barrier coatings for gas turbine blade under bending", International Journal of Turbo and Jet Engines, vol. 17, **(2000)**, pp. 1-24.
[4] A. K. Ray and R. W. Steinbrech, "Crack propagation studies of thermal barrier coatings under bending", Journal of European Ceramic Society., vol. 19, no. 12, **(1999)**, pp. 2097-2109.
[5] W. J. Brindley and R. A. Miller, "Thermal barrier coating life and isothermal oxidation of low-pressure plasma-sprayed bond coat alloys", Surface Coating Technology, vol. 43/44, **(1990)**, pp. 446-457.
[6] C. H. Liebert and R. A. Miller, "Ceramic thermal barrier coatings", Ind. Eng. Chem. Prod. Res. Dev., **(1984)**, pp. 334–349.
[7] K. Kokini, C. D. Choules and Y. R. Takeuchi, "Thermal fracture mechanisms in ceramic thermal barrier coatings", Journal of Thermal Spray Technolology, JTTEE5, ASM International, vol. 6, no. 1, **(1997)**, pp. 43-49.
[8] L. Lelait, S.C. AlperineDiot and M. Mevrel, "Thermal barrier coatings: Micro structural investigation after annealing", Materials Science and Engineering: A, vol. 121, **(1989)**, pp. 475-482.
[9] K. Kokini and Y. R. Takeuchi, "Initiation of surface cracks in multilayer ceramic thermal barrier coatings under thermal loads", Materials Science and Engineering: A, vol. 189, no. 1–2, **(1994)**, pp. 301-309.
[10] K. M. Godiwalla, N. Roy, S. Chaudhuri and A. K. Ray, "Investigation and modeling 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, **(2001)**, pp. 77-103.
[11] N. Roy, K. M. Godiwalla, S. Chaudhuri and A. K. Ray, "Simulation of bond coat properties in thermal barrier coatings during bending", High Temperature Materials and Processes, vol. 20, no. 2, **(2001)**, pp. 103-116.
[12] C.-C. Chiu and E. D. Case, "Elastic modulus determination of coating layer as applied to layered ceramic composites", Material Science Engineering: A, vol. 132, **(1991)**, pp. 39-47.
[13] D. R. J. Owen and E. Hinton, "Finite Element in Plasticity", Pineridge Press Limited: Swansea, UK, **(1980)**.
[14] W. J. Brandle, H. J. Grabke, D. Toma and J. J. Krueger, "The oxidation behavior of sprayed MCrAlY coatings", Surface Coating Technology, vol. 86/87, no. 1, **(1996)**, pp. 41-47.
[15] N. Roy, K. M. Godiwalla, E. S. Dwarakadasa, A. K. Ray, "Elasto-plastic deformation in thermal barrier coated superalloys", Scripta Meterialia, vol. 51, no. 7, **(2004)**, pp. 739-743.
[16] B. Gupta, B. Gopalkrishnan, J. Yadhav and B. Saha, "Aerospace Materials with General Metallurgy for Engineers", 2nd vol., Aeronautical Research and Development Board, S. Chand and Company Ltd., New Delhi, India, **(1996)**.
[17] A. K. Ray, S. R. Singh, J. Swaminathan, P. K. Roy, Y. N. Tiwari, S. C. Bose and R. N. Ghosh, "Structure Property Correlation Study of a Service Exposed First Stage Turbine Blade in a Thermal Power Plant", Materials Science and Engineering, vol. 419, **(2006)**, pp. 225–232.
[18] Z. Huda, "Development of heat-treatment process for P/M super alloys for turbine blades", Mater, vol. 28, no. 5, **(2007)**, pp. 1664–1667.
[19] M. P. Boyce, "The gas turbine handbook", 2nd ed. Houston, Texas: Gulf Professional Publishing, **(2002)**, pp. 411.
[20] C. T. Sims, "Non metallic Materials for gas turbine engines: are they real?", Advanced Material Processes, vol. 139, no. 6, **(1999)**, pp. 32-39.
[21] V. N. B. Rao, I. N. N. Kumar and K. B. Prasad, "Failure analysis of gas turbine blades in a gas turbine engine used for marine applications", International Journal of Engineering, Science and Technology, vol. 6, no. 1, **(2014)**, pp. 43-48.
[22] Y.-J. Xie, M.-C. Wang, G. Zhang and M. Chang, "Analysis of super alloy turbine blade tip cracking during service", Engineering Failure Analysis, vol. 13, **(2006)**, pp. 1429–1436.

