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PROBABILISTIC AND DIAGNOSTIC METHODS TO DETERMINE THE MULTIPLE FAILURE MECHANISMS OF HPT 1ST STAGE MARINE GAS TURBINE BLADE.

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Abstract
The failure analysis of high pressure turbine (HPT) blade belonging to 30 MW gas turbine used in marine applications is presented. Before failure, the turbine blade under evaluation was operated for about 10000 hours while its service life was expected to be around 15000 hours. The gas turbine blade was made of Nickel based super alloy and was manufactured by investment casting method. An attempt has been made to analyze the causes and modes of failure of a gas turbine blade. During operation, the turbine blade is subjected to large centrifugal forces and operated at elevated temperatures in corrosive environmental attack such as oxidation, hot corrosion and sulphidation etc. The investigation includes the activities like visual inspection, determination of material composition, microscopic examination, metallurgical analysis and Mechanical analysis. Metallurgical examination was carried out to diagnose the possible causes of blade failure of micro structural damage due to blade operation at elevated temperatures. The thermal-structural finite element analysis was performed on the turbine blades using ANSYS 14.0 software. From the results it was observed that, the temperatures are below the melting point of blade material. It was also 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 is concluded that the turbine blade failure might be caused by multiple failure mechanisms such as hot corrosion & erosion and fatigue. Hot corrosion could havebeen reduced the thickness of the blade material and thus weaken the blade. This reduction of the blade thickness reduces the fatigue strength which ultimately led to the failure of the turbine blade.

Keywords: *Marine gas turbine blade, Super alloy, failure analysis, Metallurgical examination, Mechanical analysis.*

INTRODUCTION

For the past few decades, the operating temperatures of gas turbine engines have been on the rise to obtain higher power output and thermal efficiency as it is understood that the efficiency of gas turbine is a direct function of turbine inlet temperature (TIT)[1].During service, high pressure turbine (HPT) blades undergo various types of time-dependent degradation due to exposure in the operating environment. These (HPT) first stage blades are the most important rotational components of gas turbine engine and are subjected to high mechanical stresses and are operated at elevated temperatures in aggressive environments [2-16]. The gas turbine blades principally made of Nickel-base super alloys. The excellent thermal stability, tensile and fatigue strengths, resistance to creep and hot corrosion, and micro structural stability possessed by nickel-based super alloys render the material an optimum choice for application in turbine blades [17-19]. Turbine blades were considered as the critical components of the gas turbine engines in which failures occurs frequently and failures in the turbine blades 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 failure in gas turbine engines were only due to blading problems and attempts were being made to improve the life of turbine blades [20]. Hot

section blades typically fail because of creep, fatigue including both low cycle fatigue (LCF) and high cycle fatigue (HCF), oxidation, corrosion, Erosion and foreign object damage [21]. Contributing factors often include environmental attack, sulphidation 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 turbine blades are operated at elevated temperatures in this type corrosive environment, cause 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 the deposition of alkali metal sulfates on the surface of the blade and resulting in the hot corrosion attack [22].

Hot corrosion is an accelerated damage phenomenon that occurs when high temperature turbine blades 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:

$$4NaC1 + 2SO_2 + 2H_20 + 0_2 \rightarrow 2Na_2SO_4 + 4HC1 \quad (1)$$

Hot corrosion on turbine blades can be intensified by the presence of vanadium, which produces V_20_5, in combination with the alkalis, while in molten state, can aggressively dissolve metal oxides. High temperature hot corrosion also known as Type I corrosion, which occurs in the approximate temperature range of 825°C to 950°C [20]. Fig 1 shows the micro structure of the surface of the blade material near the tip which has suffered from the hot corrosion.

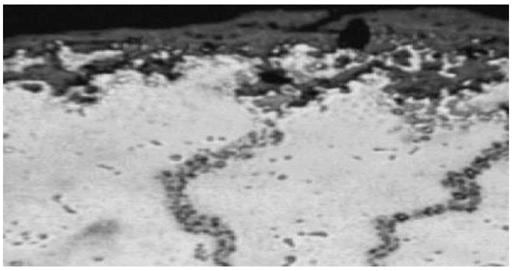


Fig.1. Type I hot corrosion, grain boundary diffusion

Low temperature hot corrosion (LTHC) also known as Type II hot corrosion which occurs during the approximate temperature range of 700°C to 800°C. From the Fig.2, it is noticed that the pitting attack is typically nonuniform with layered type corrosion scales. No intergrannular attack is found in the base metal. Very little sulphide formation within the metal is observed. Fig 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 [20].

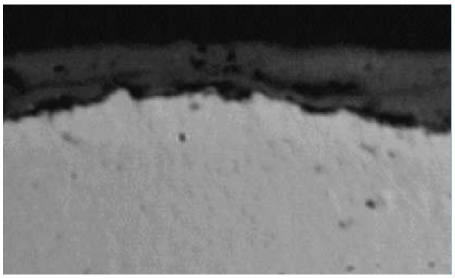


Fig. 2. Type II hot corrosion, no grain boundary diffusion

Previously some work had been carried out on failure of turbine blade through metallurgical examination [23]. In the present paper, an attempt has been made to investigate the causes of high pressure turbine (HPT) 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, the 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. In this research paper, the failure analysis of gas turbine blades has been carried out in the following two ways to predict the causes and modes of failure.

- Metallurgical analysis and
- Mechanical analysis

Metallurgical examination of a turbine blade includes the activities such as determination of material composition, visual inspection and microscopic examination. Metallurgical examination has been 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 [21].Specimens were collected from different regions of the blade to carry out the metallurgical examination.

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 of the gas turbine blade. Structural and thermal analysis of the turbine blade under evaluation is carried out using ANSYS 14.0.

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. Static analysis was carried out to know the mechanical stresses, strains and elongation experienced by the gas turbine rotor blades. Thermal analysis was carried out to know the thermal stresses and the temperature distribution.

1. Back ground data

It was reported that the HPT turbine blades under investigation were made of Nickel-Base super alloys and were manufactured by investment casting method.The composition of HPT turbine blade is shown in table.1. The blades under evaluation were the first stage blade of a 30 MW gas turbine engine used for marine application with a turbine gas inlet temperature of around 950^{0}C. It was observed that the blades were damaged during periodic service.

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

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

Fig. 3: High pressure temperature (HPT) 1st stage gas turbine blade.

2. 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 super alloy. 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.

3. MODELING & FINITE ELEMENT ANALYSIS OF GAS TURBINE BLADE.

4.1 Modeling of a HPT gas turbine blade

Reverse Engineering (RE) is being applied to generate 3D surface data of turbine blade. The data to make real model of a turbine blade is obtained using Coordinate Measuring Machine (CMM). The 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 R21is shown in Fig.4.

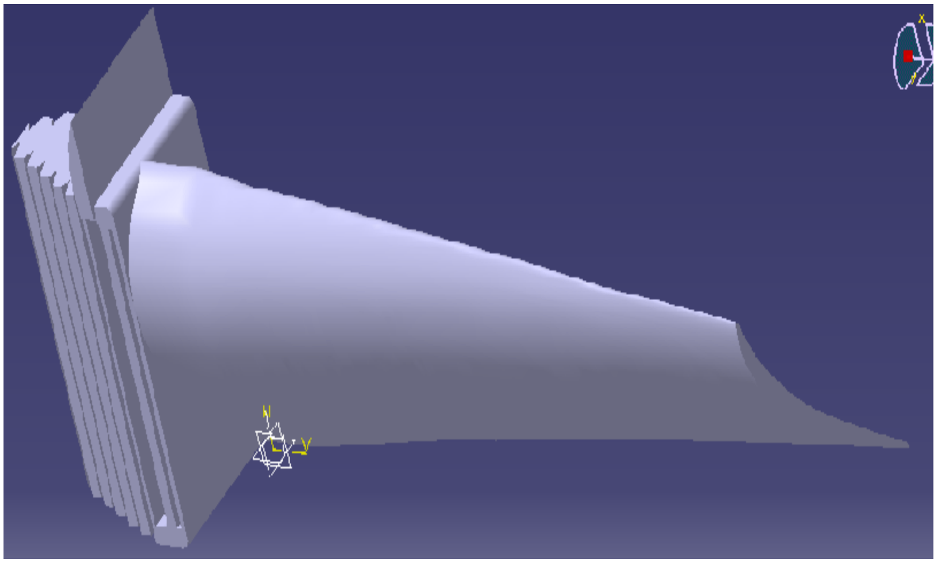


Fig. 4: Geometric model of gas turbine blade using CATIA V5 R21

4.2Finite element analysis of gas turbine blade.

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 turbine blade has been analyzed for its thermal and structural performance using ANSYS 14.5. One blade is taken into consideration for analysis as all 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 structural analysis has been carried out to know the mechanical stresses, strains and elongation experienced by the gas turbine rotor blade. In this analysis the gas forces impinged on the blade are assumed to be distributed evenly and 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.

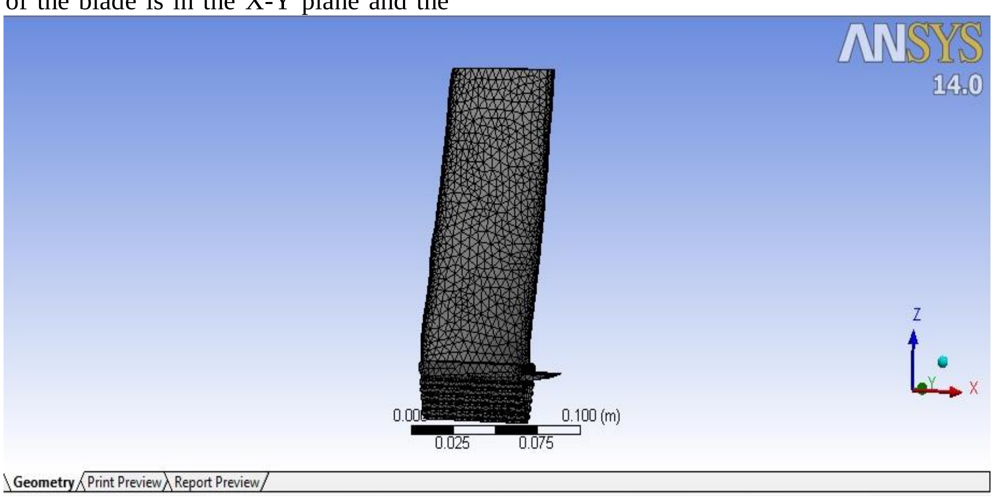


Fig. 5: Meshing of gas turbine blade under analysis

Tangential forces (Ft) =1260 N

Axial force (Fa) = 320 N

Centrifugal force (Fc) = 169164N

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

4. RESULTS AND DISCUSSIONS

5.1. Quantitative Examination of blade material

From the results of spectra chemical test of the blade material, it was found that the blade composition was also consists of 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 is attributed to the presence of the elements like sulfur and silicon [24].

5.2 Macroscopic Inspection of a turbine blade

The macroscopic features of the turbine blade were observed by visual examination. Very rough surface was noticed in the region, close to the root of the blade, and exhibited some colour change shown in Fig.6 (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 [25]

From the Fig. 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) [26]. 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 [25].

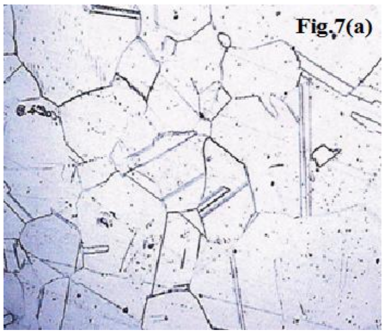
Based on the visual observation and material verification, it was concluded that there was a formation of sulphidation on the Turbine blade surface. Sulphidation is an important contributing factor to the failure of turbine blades especially in the turbines operating in marine environment. Fig.4(c) depicts 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 thus leads to high cycle fatigue and resulted in the reduction in blade life time [20].

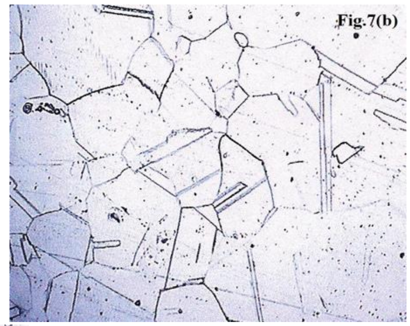
Fig.6 (a). Rough surface of the blade at the root, (b). Surface of the blade near its tip which shows some green coloration, (c). Pressure side of the blade showing the damage due to hot corrosion.

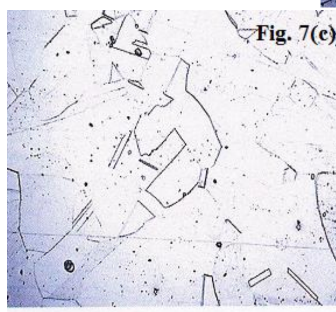
5.3. Micro structural evaluation of turbine blade material

To analyze the causes and modes 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 Fig.7 (a), in the mid span (airfoil region) Fig.7 (b) at the tip of the blade

Fig.7(c). 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.







MAGNIFICATION : 100 X

Fig 7. Micro-structure of turbine blade (a) at the root. (b) at the mid span and (c) at the tip of blade

It has been 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. Dispersed carbide particle were found in the grain boundaries of the matrix. In general, this type of micro-structure is common for Nickel-Based super alloys. The root of the blade was considered as cold zone which normally does not suffer considerable changes in its micro-structure. This type of micro-structure indicates that the root material of the blade was not exposed to the high temperatures. 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 well within the permissible limits and the 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, the carbides were decorating the grain boundaries. This micro-structure was almost similar to that of root and mid span of the blade. It emphasizes that there was no evidence of micro structural damage noticed due to operation of a blade at elevated temperatures. These results indicate 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.

5.4 MECHANICAL ANALYSIS

Exhaust gases from the combustor are directed through the turbine in such a manner that the hottest gases impinge 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 aerofoil can severely rub into the non-rotating shroud causing a ‘‘tip-rub’[27].

Mechanical analysis of a gas turbine blade consists of activities such as Reverse Engineering (RE), modeling of a turbine blade using CATIA V5 R21 software and analysis of a gas turbine blade using ANSYS14.5Structural and thermal analysis of the HPT blade under evaluation has been carried out using ANSYS 14.5. The centrifugal, axial and tangential forces acting on the blade are considered as loads in structural analysis.Structural analysis has been carried out to determine the mechanical stresses, strains and elongations experienced by the HPT blades of a gas turbine during service.Thermal analysis has been carried out to determine the thermal stresses such as the temperature distribution of the gas turbine HPT blades. The temperatures of the blade and disc were non-uniform, inducing thermal stresses by differential thermal expansion.The maximum stresses and elongations and maximum temperature induced in the turbine blade materials are within the safe limits. Maximum elongations are observed at the blade tip sections and minimum elongations at the root of the blade.

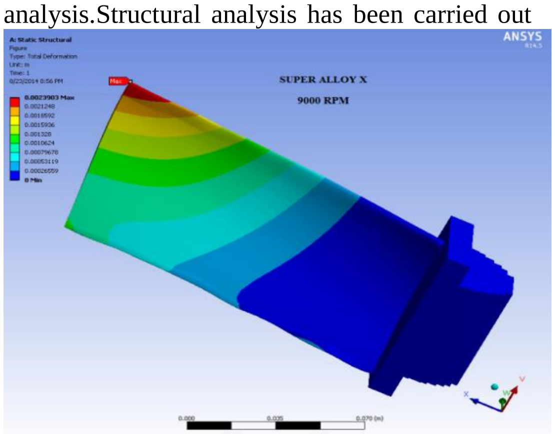


Fig. 8.1 shows deformation produced in the turbine blade due to action of all forces such as gas and centrifugal forces. It is observed that the maximum deformation of 0.00239 m occurs at the tip section of turbine blade material and the minimum occurs at the root section. There was no evidence of rubbing between tip of the turbine blade and casing, indicating that the elongation is within the limit.

Fig 8.1 : Deformation of the turbine blade due to gas pressure and combined loading.

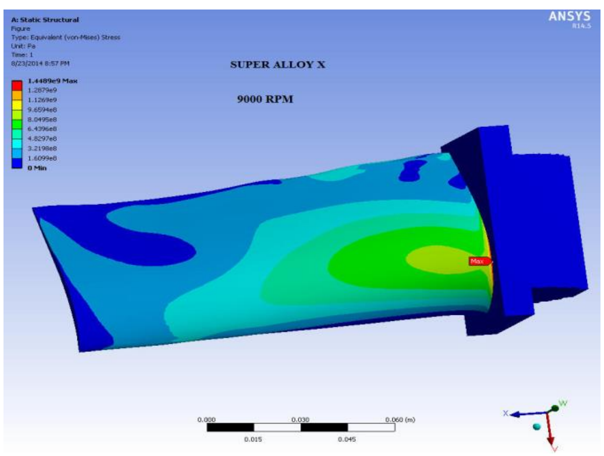


Fig. 8.2 shows the stress distribution in the turbine blade due to action of all forces such as gas and centrifugal forces. It is observed that the maximum stress of 965 N/mm^2 occurs at the root section and on the pressure side of gas turbine bladewhich is within the yield strength of the material. Minimum stress occurs at the tip of the turbine blade section.

Fig 8.2 : Stress Distribution in the turbine blade due to gas pressure and combined loading

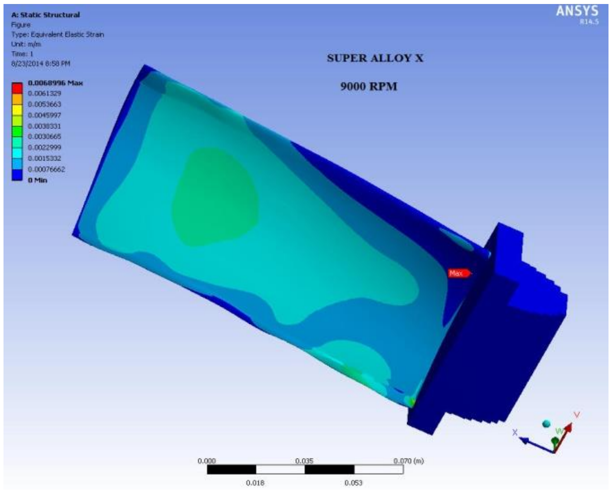


Fig 8.3 shows the Strain distribution in the HPT turbine blade due to action of all forces such as gas and centrifugal forces. It is observed that the maximum strain of 0.0053m/m occurs at the root section and on the pressure side of gas turbine blade. Minimum strain occurs at the tip section of the turbine blade section.

Fig 8.3 : Strain distribution in the turbine blade due to gas pressure and combined loading.

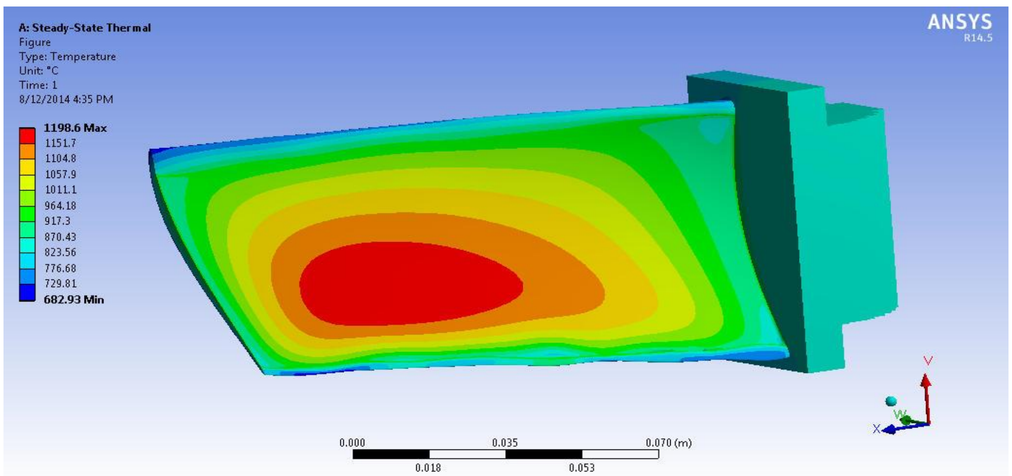


Fig 8.4: Temperature distribution in the turbine blade.

Fig 8.4 shows the Temperature distribution in the turbine blade made of Nickel based superalloy-X due to temperature gradient and heat flux. It has been observed that maximum temperature of 1198.6 ^{0}C occurred near the tip section and minimum temperature occurred at the root of the turbine blade. The maximum temperature induced in the turbine blade is well within its melting temperatures of the turbine blade material.

5. Conclusions

The failure analysis was carried out on a 30 MW gas turbine engine used for Marine applications. Its blades were made of Nickel based super alloy to sustain high temperature conditions, and other corrosive environmental conditions. Metallurgical analysis integrating mechanical analysis has been carried out to evaluate the causes and mechanisms of turbine blade failures. 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. Also from the results of structural and thermal analysis of turbine using ANSYS 14.5 on turbine blade, it is concluded that the deformations and temperatures are well within the permissible limits. This indicates the turbine blades were operated in designed/normal operating temperature conditions.

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 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. 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).

Maximum stresses and strains are observed near the root of the turbine blade and upper surface along the blade roots. The maximum stress of 965 N/mm^{2}occurs at the trailing edge nearer to the root of the blade exceeds the yield stress of the material and this might lead to the failure of the turbine blade. At all other parts of turbine blade, the stresses induced are within the same limits.

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 of hot corrosion and fatigue. 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 reduced the fatigue strength of the blade which finally the led to the failure of the turbine blade.

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