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# Selection of a Suitable Material and Failure Investigation on a Turbine Blade of Marine Gas Turbine Engine using Reverse Engineering and FEA Techniques

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***Abstract***

*Turbine blades are considered to be the heart of turbine and play a vital role in extracting energy from high temperature and high pressure gases. Without blades there would be no power and the slightest fault in blading would mean a reduction in efficiency and costly repairs. In this regard, an attempt has been made to analyze the failed marine gas turbine blade. Static structural and Steady state thermal analyses have been analyzed using ANSYS 14.5 to predict the probable conditions which leads blade failure. To investigate the causes of high pressure temperature (HPT) turbine blade failures, a turbine blade of 30 MW gas turbine engine intended for operation onboard ship has been considered for the analysis. Before failure, this gas turbine blade was operated for about 10000 hours while its service life was expected to be around 15000 hours. To improve the life time of a blade, prediction of failure criteria has been analyzed. In addition, a comparative analysis has also been made to determine the strength and suitability of a HPT blade made of Nickel based super alloy X under examination. This material has been compared with other two materials such as Nimonic alloy 80A and Inconel 625. Based on the results of comparative study, it is concluded that Nickel based super alloy X can be a suitable material for the manufacturing of gas turbine blades.*

***Keywords:*** *Reverse Engineering, CATIA, ANSYS, Static Structural analysis, Steady state thermal analysis*

## 1. Introduction

Gas turbines play a major role in aviation, land based power generation and marine applications owing to their high power-to-weight ratios and compactness when compared to other conventional power generating units. The purpose of gas turbine technology is to extract the maximum quantity of energy from the working fluid to convert it into useful work with maximum efficiency by means of a plant having maximum reliability, minimum cost, minimum supervision and minimum starting time. Turbine Blades are the most important components in a gas turbine and are responsible for extracting energy from high temperature gases. It is observed that 42% of turbine failure occurs due to blade failure. The turbine blades are mainly affected due to static loads and elevated temperature. Due to these reasons there emerged a great importance in predicting the life of a gas turbine blade therefore the static and thermal analysis of turbine blades is carried out. In this paper the first stage rotor

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blade made up of Nickel based super alloy Grade X is created in CATIA V5 R21 software and then this model has been analyzed using ANSYS 14.5. The gas forces namely tangential and axial forces are determined by constructing velocity triangles at inlet and exit of rotor blades. Centrifugal forces are calculated by applying the angular velocity to the turbine blade rotor. The convective heat transfer coefficients were calculated using the heat transfer empirical relations taken from the heat transfer design data book. HPT blade has been analyzed using ANSYS 14.5 for the static and thermal stresses [1-4].

## 2. Reverse Engineering

Where there is no 3D data of geometries available, the reverse engineering process comes into picture. RE provides immediate feedback and generates dimensional report with good precision and accuracy. Suppose in any problem predictions, if only one part is available it should be crucial for validation. The component must be carefully examined and the necessary method of RE should be adopted. The features which can be measured manually are taken with the help of available measuring devices like steel rule, vernier caliper, and depth gauge etc. The geometries such as free formed surfaces, complex contours, and irregular 3D surfaces are to be measured through special techniques like scanning, optical and digitization techniques (CMM) [1].

Material: Nickel based Super alloy grade X

Turbine inlet temperature : around 950 $^0$C

Turbine exit temperature : around 700 $^0$C

Working Pressure : 10 bar

RPM of the rotor : 4000 - 9000

**Figure 1. Failed Maine First Stage HPT Gas Turbine Blade**

## 3. Literature Review

Numerous researchers attempted the problem of turbine blade failures in order to optimize the performance.

Prasad Gudimetla [1] presented the Reverse engineering process and its importance. In this paper he presented a framework which successfully uses a combination of Reverse Engineering (RE) and finite element analysis (FEA) to model, analyze and optimize the material properties. Turbine blades are subjected to a combination of high operating temperatures, centrifugal and bending stresses due to impulsive loads along with erosive/corrosive effects during operation. These operating conditions make the blades most susceptible to failure and demand periodic inspection which adversely affects the overall operational costs.

P. V. Krishnakanth [2] Withstanding of gas turbine blades for the elongations is a major consideration in their design because they are subjected to high tangential, axial, centrifugal forces during their working conditions. Several methods have been suggested for the better enhancement of the mechanical properties of blades to withstand these extreme conditions. Their study summarizes the design and analysis of Gas turbine blade, on which CATIA V5 is used for deign of solid model using spline and extrude options. ANSYS 11.0 software is used for the analysis of F.E. model generated by meshing of the blade using the solid brick element present in the ANSYS software itself and thereby applying the boundary condition. Their study specifies how the program makes effective use of the ANSYS pre-processor to analyze the complex turbine blade geometries and apply boundary conditions to examine steady state thermal & structural performance of the blade for N 155, Hastealloy x & Inconel 625 materials. Finally stating the best suited material among the three from the report generated after analysis.

G. Narendranath [4] The first stage rotor blade of the gas turbine has been analyzed using ANSYS 9.0 for the mechanical and radial elongations resulting from the tangential, axial and centrifugal forces. The gas forces namely tangential, axial were determined by constructing velocity triangles at inlet and exit of rotor blades. The material of the blade was specified as N155 which is iron based super alloy and structural & thermal properties of gas at room temperatures are taken. The turbine blade along with the groove blade is modeled with the 3D-Solid Brick element. The geometric model of the blade profile is generated with splines and extruded to get a solid model in CATIAV5R15. The first stage rotor blade of a two stage gas turbine has been analyzed for structural, thermal and modal analysis using ANSYS 9.0 Finite Element Analysis software.

## 4. Modeling and Analysis

### 4.1. CATIA Modeling

The turbine blade has been designed using Co-ordinate Measuring Machine (CMM) data. The blade model profile is generated by using CATIA software. Key points are created along the profile in the working plane using excel macros. The points are joined by drawing B spine curves to obtain a smooth contour. The contour (2D model) is then converted into area and then volume (3D model) was generated by extrusion. The hub is also generated similarly. These two volumes are then combined into single volume [1, 6].

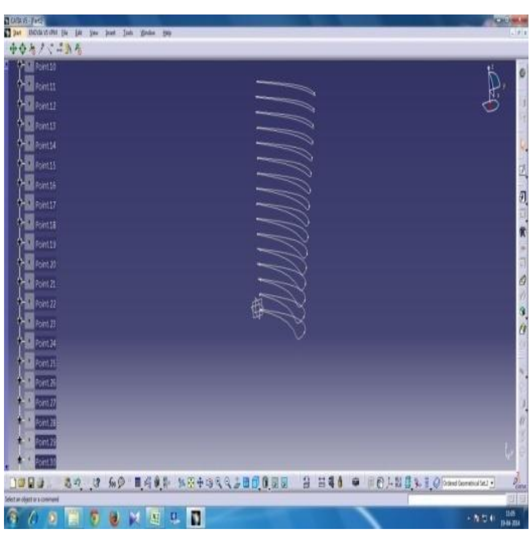

**Figure 2. Key Points and Splines**

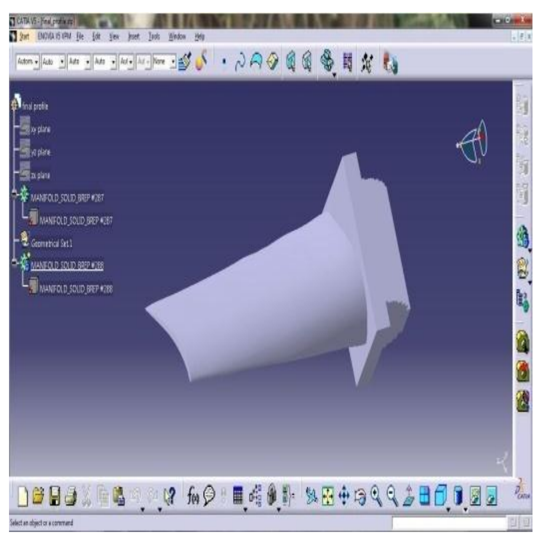

**Figure 3. Blade Profile with Root**

### 4.2. FEA Technique

The gas turbine blade has to be analyzed under two categories of stresses. The first type is centrifugal stresses that act on the blade due to high angular speeds and second is thermal stresses that arise due to temperature gradient within the blade material. The analysis of turbine blade mainly consists of the following two parts: Structural and thermal analysis. The analysis is carried out under steady state conditions using ANSYS software. To evaluate the distribution of stresses, deformation, temperature and other effects during service of component it is necessary to arrest the all degrees of freedom (DOF) of a root. The phenomenon of splitting into numerous small elements is called discrimination. The predominant forces acting on the blade are observed to be gas pressure and force due to change in momentum that enables the rotation. I.e. the pressure force accompanied by axial and tangential components of the gas flow. Therefore in this paper an attempt has been made to investigate on the following areas to describe the working life [7].

### 4.3. Material Properties

**Table 1. Material Properties of Super Alloys**

| Materials | Super Alloy Grade X | Nimonic Alloy 80A | Inconel 625 |
|---|---|---|---|
| Young's Modulus (GPa) | 210 | 222 | 208 |
| Density (kg/m$^3$) | 7780 | 8190 | 8440 |
| Poisson's ratio | 0.3 | 0.35 | 0.29 |
| Thermal conductivity (W/mk) | 22 | 11.2 | 21.3 |
| Thermal expansion ($^0$C) | $10*10^{-6}$ | $12.7*10^{-6}$ | $13.1 * 10^{-6}$ |
| Yield strength (MPa) | 1175 | 1144 | 1150 |
| Melting temperature ($^0$C) | 1370 | 1340 | 1350 |

### 4.4. Boundary Conditions

The gas turbine blade was subjected to three types of loads viz., (a) an axial force acting along the x-axis $F_a$ ; (b) a tangential force along the y-axis, $F_t$ and (c) centrifugal force in the z-axis, $F_c$ . In the solution part of the ANSYS, these blade forces were applied on the node located at the *centriod* of the blade. The gas forces namely tangential, axial were determined by constructing velocity triangles at inlet and exist of rotor blades and the centrifugal force due to rotation of rotor were determined by the empirical relations at different rpm's [1].

### 4.5. Summary of Forces on Turbine Blade

**Table 2. Gas Forces Acting on Turbine Blade at Various Speeds**

| Gas forces on blade ↓ | Speed (rpm) | | |
|---|---|---|---|
| | 4000 | 6000 | 9000 |
| Tangential force in Newton's | 535 | 775 | 1260 |
| Axial force in Newton's | 222.5 | 200 | 320 |

### 4.6. Centrifugal Force for different Materials at Various Speeds

**Table 3. Centrifugal Forces Acting on Turbine Blade at Various Speeds**

| Materials ↓ | Centrifugal force at different speeds, $F_C$ in N | | |
|---|---|---|---|
| | 4000 RPM | 6000 RPM | 9000 RPM |

 

| | | | |
|---|---|---|---|
| Super alloy X | 37592 | 84578 | 190301 |
| Mnemonic alloy 80 A | 39580 | 89050 | 200364 |
| Inconel 625 | 40958 | 91759 | 206459 |

### 4.7 Meshing

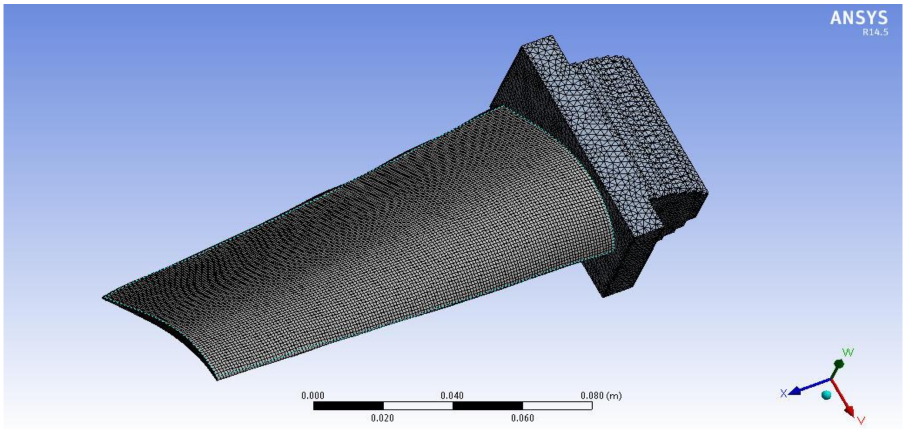


**Figure 4. Meshing of HPT Gas Turbine Blade Profile**

## 5. Static Structural Analysis at max. Speed (9000 rpm)

**Super alloy X**

***Total deformation***

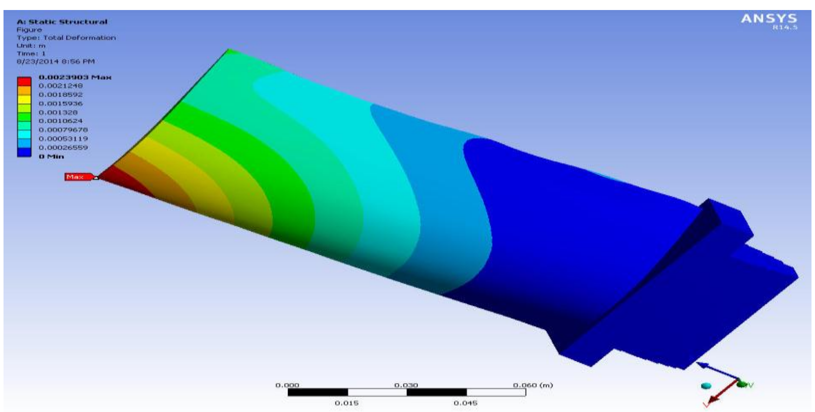


**Figure 5. Total Deformation on Turbine Blade Made of Super Alloy X**

***Von-mises Stress***

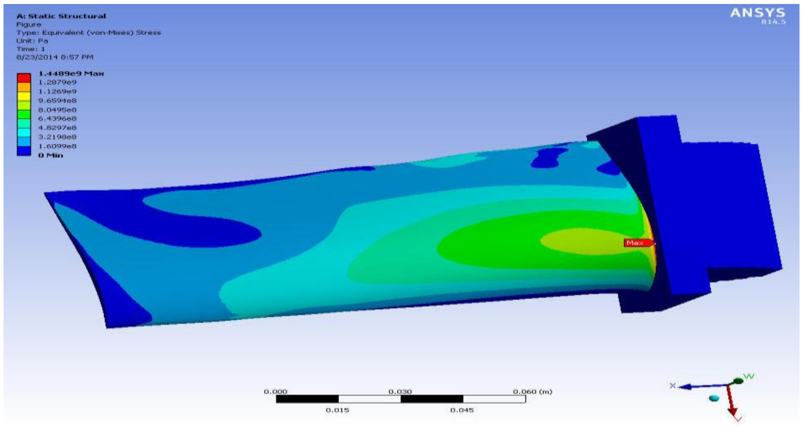


**Figure 6. Von-mises Stresses Distribution in Turbine Blade Made of Super Alloy X**

***Strain***

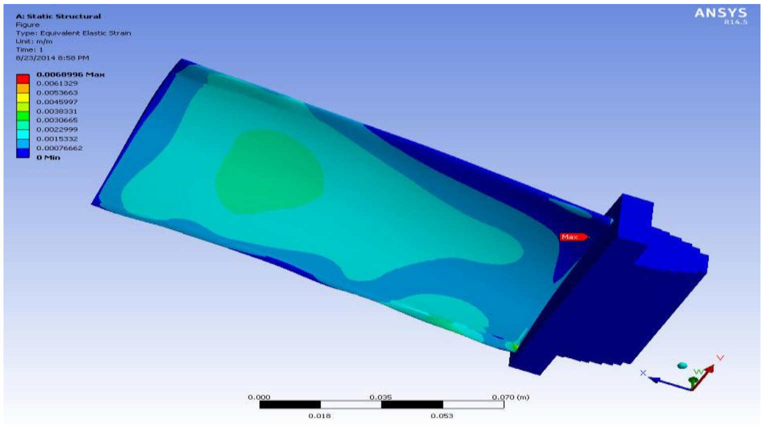


**Figure 7. Strain Induced in Turbine Blade Made of Super Alloy X**

**Nimonic alloy 80A**

***Total Deformation***

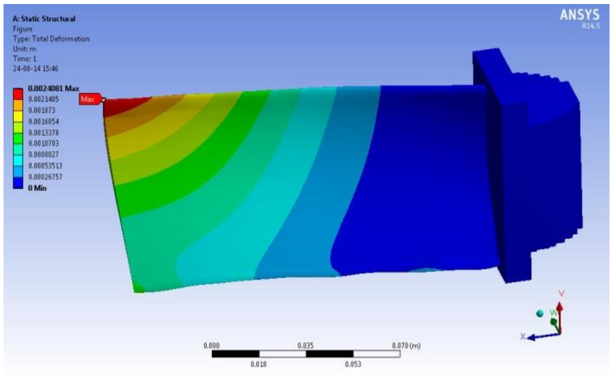


**Figure 8. Total Deformation on Turbine Blade Made of Nimonic alloy 80A**

***Von-mises Stress***

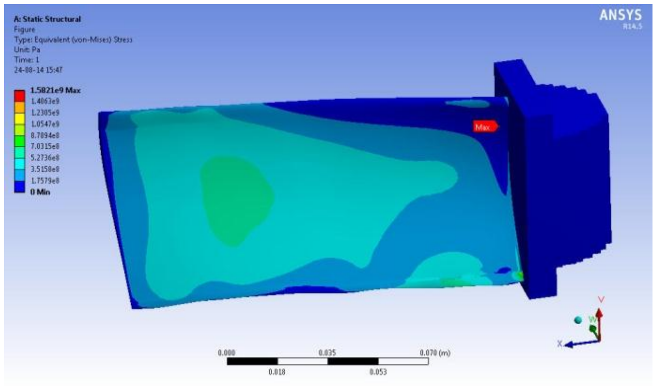


**Figure 9. Von-mises Stresses Distribution in Turbine Blade made of Nimonic alloy 80A**

***Strain***

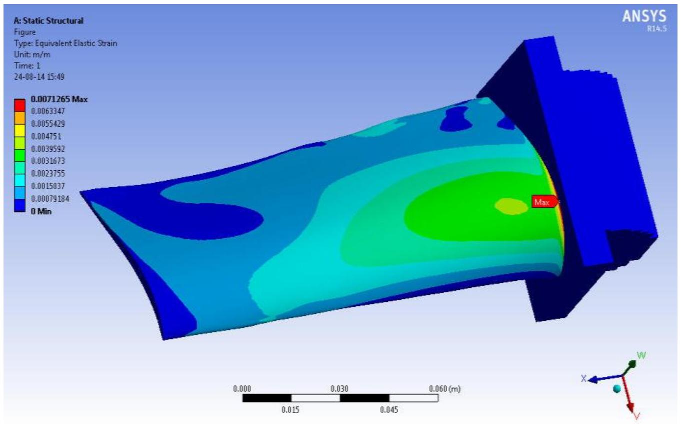


**Figure 10. Strain Induced in Turbine Blade made of Nimonic Alloy 80A**

**Inconel 625**

***Total Deformation***

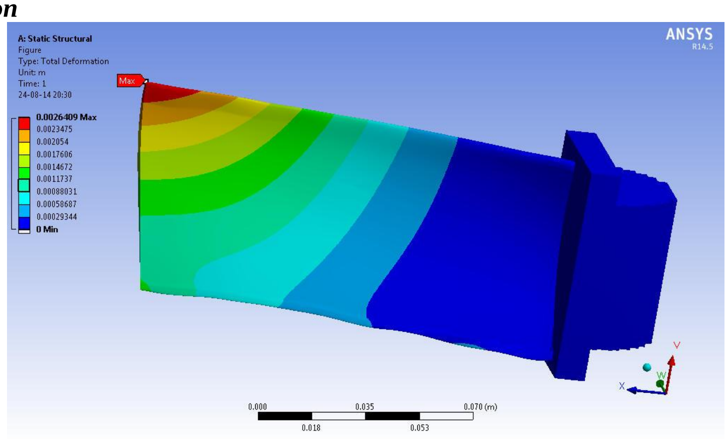


**Figure 11. Total Deformation on Turbine Blade Made of Inconel 625**

***Von-mises Stress***

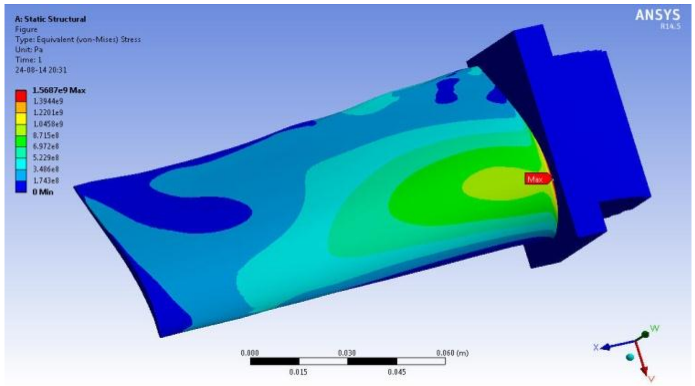


**Figure 12. Von-mises Stresses Distribution in Turbine Blade made of Inconel 625**

***Strain***

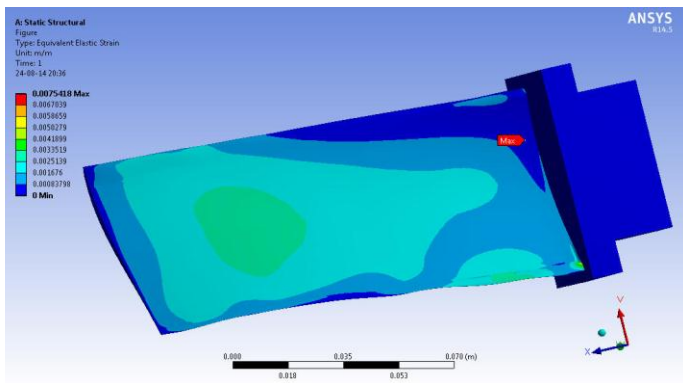


**Figure 13. Strain Induced in Turbine Blade made of Inconel 625**

## 6. Steady State Thermal Analysis

***Temperature distribution***

***Super alloy X***

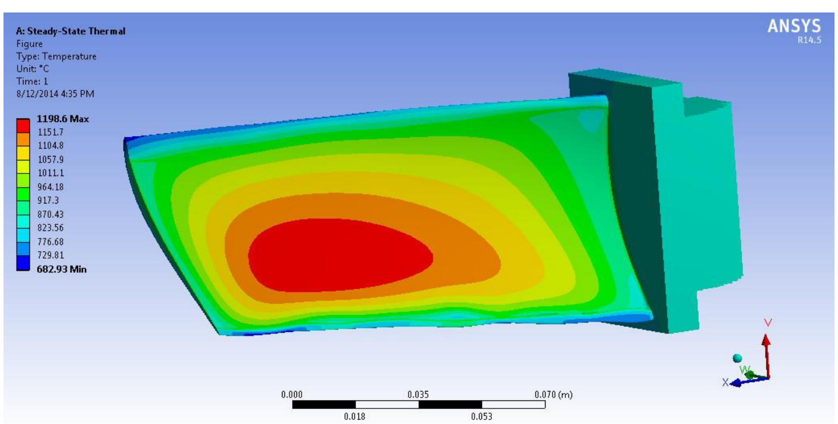


**Figure 14. Temperature Distribution in Turbine Blade Made of Super Alloy X**

*Nimonic alloy 80A*

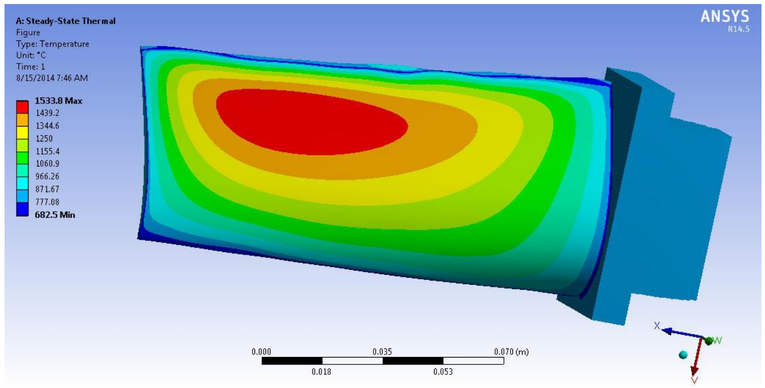


**Figure 15. Temperature Distribution in Turbine Blade Made of Nimonic Alloy 80A**

*Inconel 625*

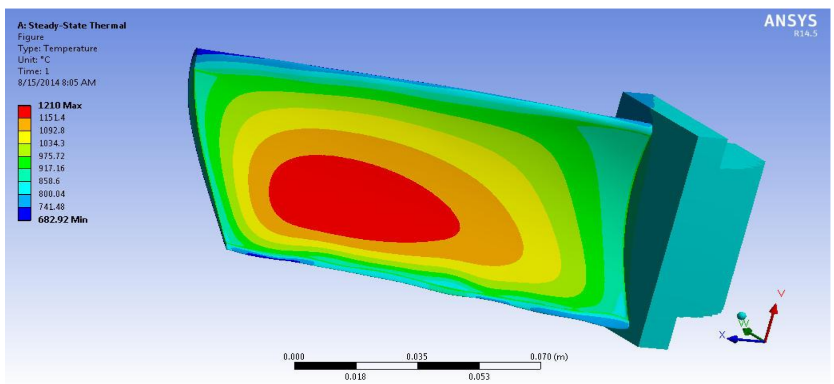


**Figure 16. Temperature Distribution in Turbine Blade made of Inconel 625**

## 7. Results and Discussions

### 7.1. Results of Structural Analysis

**Table 4. Variations in Mechanical Parameters of Different Materials at Various Speeds**

| | Rotation in rpm ↓ | Turbine blade Material | | |
|---|---|---|---|---|
| | | Super alloy X | Nimonic alloy 80 A | Inconel 625 |
| Total Deformation (m) | 4000 | 0.00039669 | 0.00040487 | 0.00044774 |
| | 6000 | 0.0010111 | 0.0010222 | 0.0011218 |
| | 9000 | 0.0023903 | 0.0024081 | 0.0026409 |
| Von- | 4000 | 267.62 | 292.51 | 292.49 |

| | | | | |
|---|---|---|---|---|
| | 6000 | 629.44 | 687.98 | 682.73 |
| | 9000 | 965.59 | 1054.7 | 1045.8 |
| Strain | 4000 | 0.0012744 | 0.0013176 | 0.0014062 |
| | 6000 | 0.0029973 | 0.003099 | 0.0032824 |
| | 9000 | 0.0068996 | 0.0071265 | 0.0075418 |

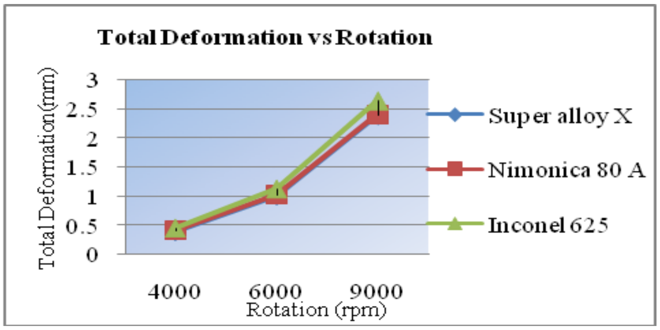


**Figure 17. Total Deformations Induced in Turbine Blades made of Different Materials at Various Speeds**

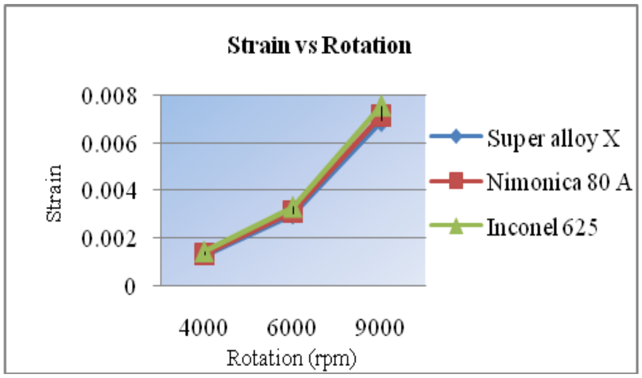


**Figure 18. Strains Induced in Turbine Blades Made of Different Materials at Various Speeds**

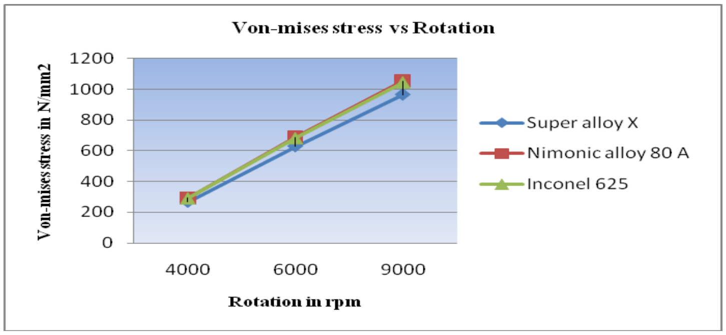


**Figure 17. Equivalent Stress Distribution in Turbine Blades made of Different Materials at Various Speeds**

 

The structural - thermal finite element analysis was performed for the first stage HPT turbine blade with different rotational speeds *i.e.*, 4000, 6000 and 9000 rpm's by specifying structural and thermal loads with an objective of finding failure criteria of existing blade material (Super alloy X) and further to know the preferred material for the best performance. Based on the results obtained from the ansys software the graphs *i.e.*, Figure 17 (Total deformation vs Rotation), Figure 18 (Strain vs Rotation), Figure 19 (Von-mises stress vs Rotation) were plotted. The von-mises stress are proportionally increasing with increase in rotation (RPM) and the obtained von-mises stresses are within the safe limits for three Super alloy materials which are considered in this study. Total deformations are closely varying and maximum strains are developed at joint section of root and blade volumes.

### 7.2. Results of Thermal analysis

**Table 5. Maximum Temperature Obtained in Turbine Blade Made Different Materials**

| Super alloy Material | Melting temperature($^0$C) | Max.Temperature obtained($^0$C) |
|---|---|---|
| Super alloy X | 1400 | 1198.6 |
| Nimonic alloy 80 A | 1380 | 1533.8 |
| Inconel 625 | 1350 | 1210 |

It is observed that the maximum temperatures are prevailing at the leading edge of the blade. However, there is a temperature fall from the leading edge to the trailing edge of the blade. It is observed from fig14 (Super alloy X), fig 15 (Nimonic alloy 80 A) and fig16 (Inconel 625), that the blade temperatures attained for Super alloy X are marginally lower. The both Super alloy X and Inconel 625 are having maximum temperatures obtained are below their melting temperatures where as Nimonic alloy 80 A having maximum temperature distribution obtained is beyond its melting temperature.

## 8. Conclusions

- Finite element analysis results for first stage HPT blade give a complete picture of structural and thermal characteristics, which can be utilized for the improvement in the design and optimization of the operating conditions.
- The turbine blade model data under examination has been obtained using Coordinate Measuring Machine (CMM) from existing Turbine blade.
- Comparative study has been carried out on turbine blade made of different materials which are preferable for marine gas turbine rotor blade.
- From the obtained results, it is clear that the HPT turbine blade with existing material (Super alloy grade X) was not failed because of tangential, axial and centrifugal forces. The equivalent stresses obtained at max rpm (9000) are well below the safe values.
- The von-mises stresses for the blade are maximum at the joint portion where profile is attached to root.
- From the structural contours of ANSYS it can be observed that total deformations are maximum at tip portion of the blade profile.
- It is observed that the temperature distribution is uniform and maximum temperature obtained is within the melting point of turbine blade made of Nickel based Super alloy X.

- Among the three materials the Super alloy X is the best material for marine HPT rotor blade due to its less equivalent stress values at three different speeds and safe temperature distributions.

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