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ANALYTICAL COMPARATIVE STUDY OF GAS TURBINE BLADE MATERIALS USED IN MARINE APPLICATIONS USING FEA TECHNIQUES

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ABSTRACT
The turbine blades are responsible for extracting energy from the high temperature gas produced by the combustor. Operating the gas turbine blade at high temperatures would provide better efficiency and maximum work output. These turbine blades are required to withstand large centrifugal forces, elevated temperatures and are operated in aggressive environments. To survive in this difficult environment, turbine blades often made from exotic materials. A key limiting factor in gas turbine engines is the performance of the materials available for the hot section of the engine especially the gas turbine blades. In this paper, three materials such as Nimonic alloy, Super alloy and titanium aluminium have been considered for the purpose of performance analysis. The turbine blade under evaluation belongs to the first stage rotor blade of a two -stage gas turbine. The turbine blade data was obtained using CMM and its 3D solid model is created by using CATIA V5R21software. The turbine blade is analyzed for its thermal and structural performance due to the loading condition and the temperature gradients using ANSYS 14.0 software. The stresses induced in the turbine blade made up of super alloy and Nimonic 80A alloy are well within the safe limits. Finally, it could be concluded that the super alloy which is being used in manufacturing of the turbine blade of marine gas turbine engine as the best suitable material.

I. 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 society moves towards a higher dependence on technology, there will be an increased demand for gas turbine engines to produce power at higher efficiencies. The effects of globalization will further the need of the more efficient gas turbine engines for propulsion and power generation. These requirements will be met only through detailed research of the specific components of the gas turbines. The main goal of the gas turbine technology is to extract maximum amount of energy from the high temperature gases which could be achieved by improving the thermal efficiency of the gas turbine engine [1]. From the studies, it was understood that the efficiency of gas turbine is a direct function of turbine inlet temperature (TIT) and thus operating the gas turbine at elevated temperatures would provide better efficiency and specific power output [2]. A key limiting factor in early gas turbine engines was the performance of the materials available for the hot section (combustor and turbine) of the engine especially the gas turbine blades. The thermal efficiency of early gas turbines was very low because the maximum temperature of the cycle was limited by metals then available for the manufacture of components. Advancements made in metallurgy of the materials have slowly increased the thermal efficiency of the gas turbine and this is now comparable with that of steam power plants, but not with

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reciprocating internal combustion engines. In particular, achieving enhanced efficiency for marine gas turbines is a major challenge as the surrounding environment is highly aggressive. This aspect depends not only on the design but also on the selection of appropriate materials for their manufacturing. Between the two, selection of materials plays a vital role as the materials have to perform well for the designed period under severe marine environmental conditions [3]. The need for better materials of turbine blades spurred much research in the field of alloys and manufacturing techniques. The research on turbine blade materials resulted in a long list of new materials and methods that make modern gas turbines possible to operate at highest temperature.

Titanium alloy with some other elements specially aluminium is used in the manufacture of gas turbine blade as it has its high tensile strength, high corrosion resistance, density and its capability to resist creep at high temperature. Superalloys were developed since the second quarter of the 20th century as materials for elevated temperature applications and can be divided into three main groups: nickel base superalloys, cobalt base superalloys and iron base super alloys [4]. The nickel base alloys are the most widely used. 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 the application in turbine blades [5–7]. These superalloys are the standard material for hot stages of gas turbines, where blades are subjected to high mechanical stresses, elevated temperatures and aggressive environments [8–22].

In present work, three materials such as Nimonic alloy, Super alloy used for manufacture of turbine blades of a gas turbine engine meant for marine applications and titanium aluminium have been selected for the performance analysis. The chemical composition of the three materials is given in table 1.These three materials were usually being used for the manufacture gas turbine blades. Turbine blades have to be designed to withstand high temperatures, high pressure forces and large centrifugal forces. This work mainly focuses on structural and thermal analysis of three materials using ANSYS 14.0. Reverse Engineering is adopted to generate 3D surface data of turbine blade under analysis. This data was 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 due to the loading condition. 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.

II. MODELING OF GAS TURBINE BLADE

The blade under examination belongs to 1^{st} stage turbine blades of 15 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. First for creating the 3D model of the turbine blade, key points were created along the profile in the

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working plane. The points were joined by drawing B Spline curves to obtain a smooth contour. This contour was then converted into area and then into volume. Then working plane was rotated by 90º to generate the root part in the same way as the blade. These two volumes were then combined to make a single volume using union Boolean operation.

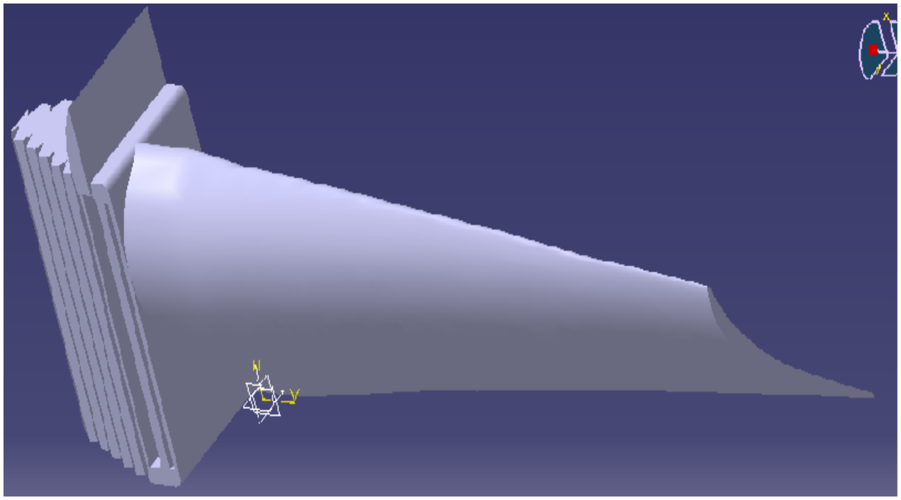

Fig 1 : Gas turbine blade model using CATIA V5 R21

III. 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.

IV. FINITE ELEMENT ANALYSIS OF GAS TURBINES BLADE

The Present work deals with the modeling and analysis of gas turbine blade. The turbine blade is analyzed for its thermal as well as structural performance due to the loading condition. The structural and thermal analysis of a gas turbine is carried out using ANSYS 14.0

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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 and in the radial direction.

Tangential forces (Ft) = 96.28N
Axial force (Fa) = 50.140N
Centrifugal force (Fc) = 9690 N (Titanium Al Alloy)
16500 N (Nimonic Alloy 80A)
15674.81 N (Super Alloy)

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

V. RESULTS AND DISCUSSIONS

The research 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 software. Three materials such as Titanium Al alloy, nimonic 80A alloy and super alloy, the material which is used in the manufacturing of marine gas turbine blade have been considered for the analysis under same operating conditions and the results are tabulated..

Table 1: Comparative values of stresses, deformations and temperatures of 3 materials.

MATERIAL	Max Stress (N/mm^2)	Maximum Deformation, (mm)	Maximum Temperature, (^{O}C)
Titanium Al Alloy	350.4	5.1	1690.8
Nimonic 80 A Alloy	362.7	2.36	1179.1
Superalloy	351.7	2.51	1164

Maximum stresses are observed at the trailing edge of blade near to the root. Nimonic 80A is having maximum stress of 362.7 N/mm^2 and Titanium is having minimum stress of 350.4 N/mm^2.

Total deformation is more at leading side of the blade at tip side. Titanium is having maximum deformation of 5.1mm and Nimonic 80A has minimum deformation of 2.36 mm.

Max temperature distribution is observed at the tip of the blade near to leading edge. Titanium Al alloy is having max temperature of 1690.8 ^{0}c and super alloy is having minimum temperature of 1164^{0}C

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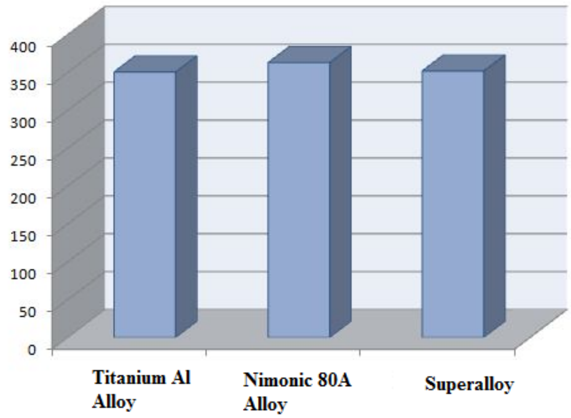

Fig 5.1 : Maximu stresses in the 3 Materials

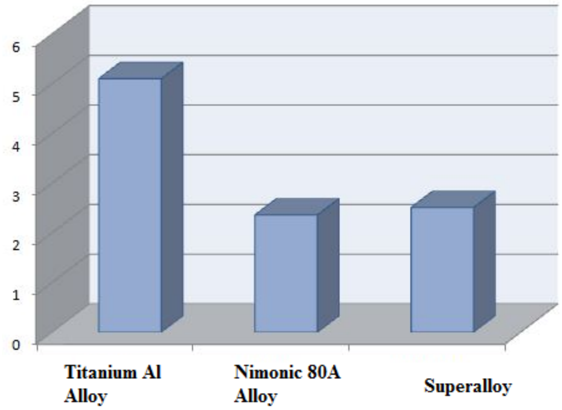

Fig 5.2 : Deofrmation in the 3 Materials

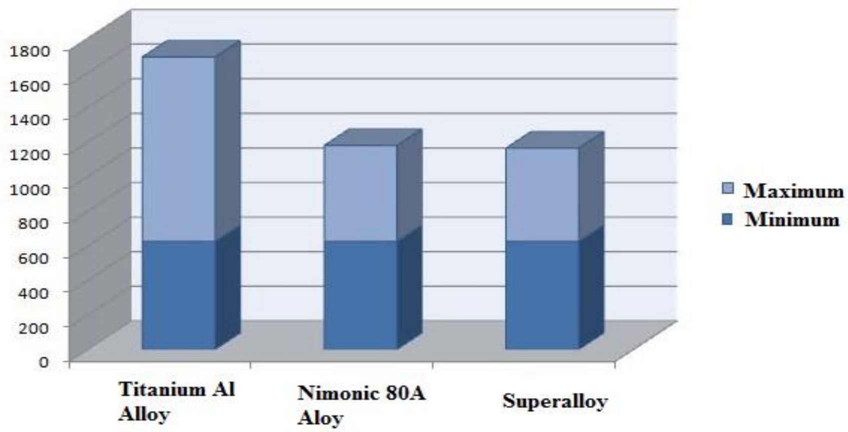

Fig 5.3 : Temperature Distribution for 3 Materials

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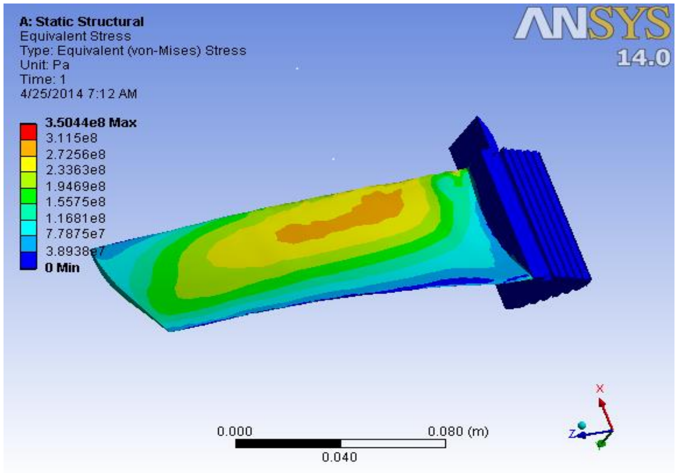
Titanium Al Alloy



.Fig 5.4 indicates the stress distribution in the turbine blade made of Titanium Al Alloy due to mechanical loads and it is observed a stress of 350.4 N/mm^2 which is maximum at leading edge near to the root of the blade and the value is minimum at the tip of the blade.

Fig 5.4 : Distribution of Stresses in the turbine blade due to mechanical loads for Titanium Al alloy

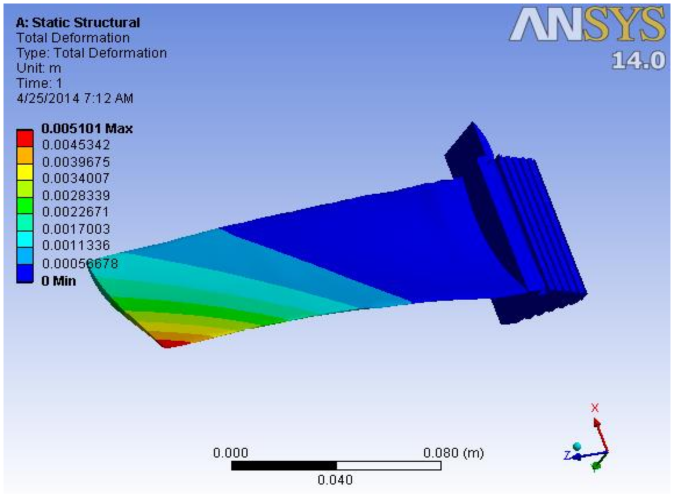


Fig 5.5 shows the deformations in the turbine blade made of Titanium Al Alloy due to forces. Maximum elongation (deformations) of 5.1 mm observed at the blade tip sections and minimum elongations at the root of the blade.

Fig 5.5 : Total deformation in the turbine blade due to mechanical loads for Titanium Al alloy

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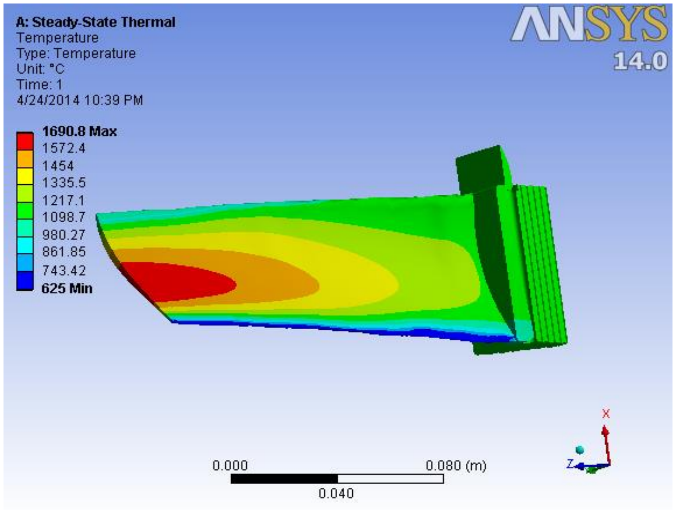

Fig 5.6 : Temperature Distribution in the turbine blade for Titanium Al alloy

Fig 5.6 shows the Temperature distribution in the turbine blade blade made of Titanium Al Alloy due to temperature gradient and heat flux. It is observed that Maximum temperature of 1179.1 ^{0}C occurs at the tip section and minimum temperature occurs at the root of the turbine blade.

Nimonic 80 A alloy

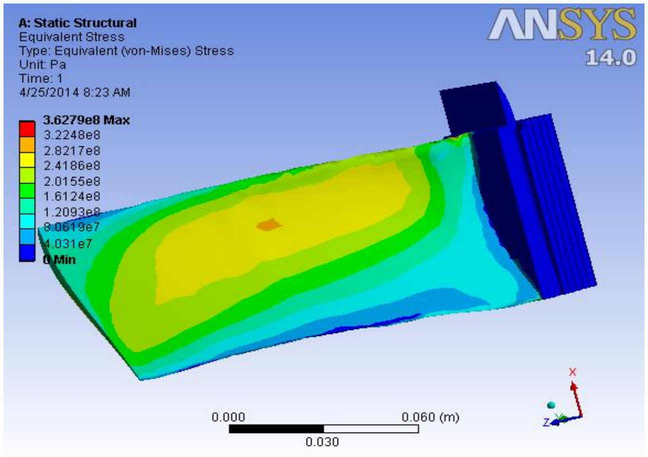

Fig 5.7 indicates the stress distribution in the turbine blade made of Nimonic 80A alloy due to mechanical loads and it is observed a stress of 362.7 N/mm^2 which is maximum at leading edge near to the root of the blade and the value is minimum at the tip of the blade.

Fig 5.7 : Distribution of Stresses in the turbine blade due to mechanical loads for Nimonic 80A alloy blade

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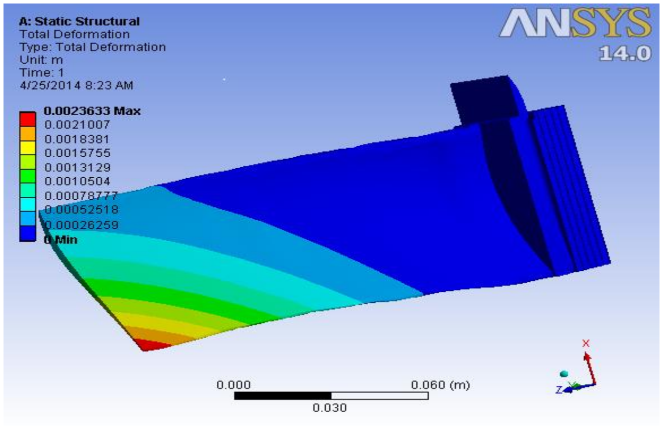

Fig 5.8 shows the deformations in the turbine blade made of Nimonic 80A alloy due to forces. Maximum elongation (deformations) of 2.36 mm observed at the blade tip sections and minimum elongations at the root of the blade.

Fig 5.8 : Total deformation in the turbine blade due to mechanical loads for Nimonic 80A alloy blade

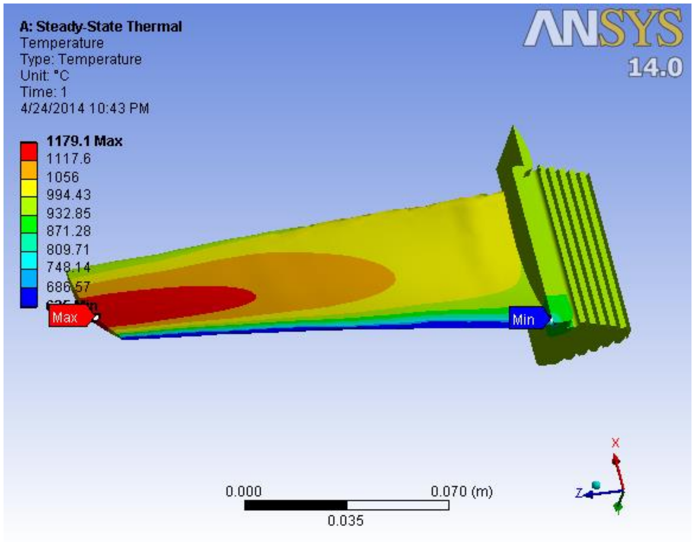

Fig 5.9 shows the Temperature distribution in the turbine blade blade made of Nimonic 80A alloy due to temperature gradient and heat flux. It is observed that Maximum temperature of 1179.1 ^{0}C occurs at the tip section and minimum temperature occurs at the root of the turbine blade.

Fig 5.9 : Temperature distribution for Nimonic 80A alloy blade

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Superalloy

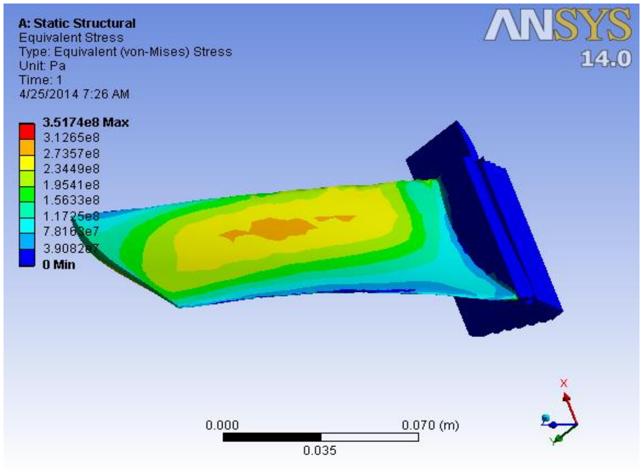

Fig 5.10 indicates the stress distribution in the turbine blade made of Superalloy used in Marine applications due to mechanical loads and it is observed a stress of 351.7 N/mm^2 which is maximum at leading edge near to the root of the blade and the value is minimum at the tip of the blade.

Fig 5.10 : Distribution of Stresses in the turbine blade due to mechanical loads for Super alloy blade.

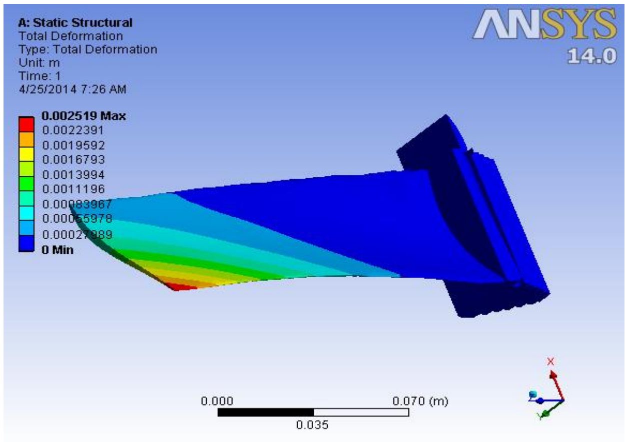

Fig 5.11 shows the deformations in the turbine blade made Superalloy used in Marine applications due to forces. Maximum elongation (deformations) of 2.51 mm observed at the blade tip sections and minimum elongations at the root of the blade.

Fig 5.11: Total deformation in the turbine blade due to mechanical loads for Super alloy blade

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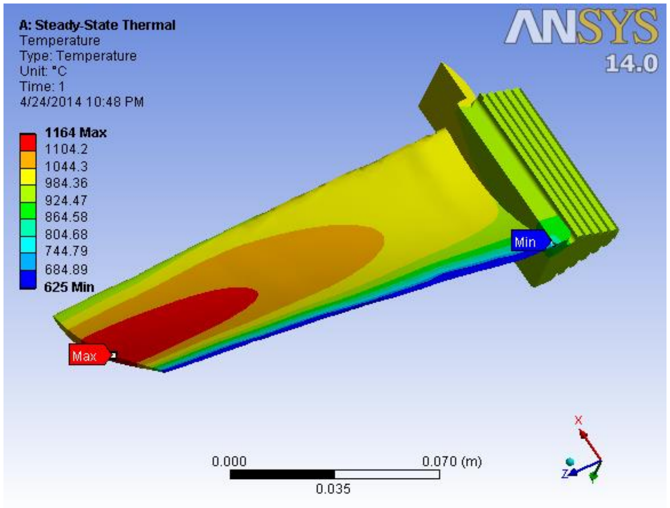

Fig 5.12 shows the Temperature distribution in the turbine blade blade made of Superalloy used in Marine applications due to temperature gradient and heat flux. It is observed that Maximum temperature of 1164 ^{0}C occurs at the tip section and minimum temperature occurs at the root of the turbine blade.

Fig 5.12 : Temperature distribution for Super alloy blade

It is observed that the stress distribution, elongations and temperature distribution patterns are same for all three materials. Maximum elongations and temperatures are observed at the blade tip section and minimum elongation and temperatures at the root of the blade. Maximum stresses are observed at the root of the turbine blade and upper surface along the blade roots three different materials of construction. Elongations and Stresses induced in the turbine blade made of Super alloy and Nimonic 80A alloy are well within in the limits and temperatures attained in these two materials are minimum compared to Titanium Al alloy.

VI. CONCLUSIONS

The main 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 and are subjected to high mechanical stresses, elevated temperatures and are operated in aggressive environments. To survive in this difficult environment, turbine blades often made from exotic materials. Three materials such as Nimonic alloy, Super alloy used for manufacture of turbine blades of a gas turbine engine meant for marine applications and titanium aluminium have been selected for the performance analysis. The turbine blade data was obtained using Coordinate Measuring Machine (CMM) and its model profile is generated by using CATIA V5R21software. The turbine blade is analyzed for its thermal as well as structural performance due to the loading condition and the temperature gradients.

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Maximum temperatures are observed at the blade tip sections and minimum temperature at the root of the blade. Temperature distribution is almost uniform and is linearly decreasing from the tip of the blade to the root of the blade section. The distribution of temperature is same for turbine blades made of three different materials. It can be seen that the temperature attained is maximum for titanium alloy and then Nimonic 80 A and lower temperature is attained for super alloy under examination.
Maximum elongations (deformations) observed at the blade tip sections and minimum elongations at the root of the blade. The maximum elongation is 5.4 mm for titanium alloy, 3.18 mm for Nimonic 80 A and 3.33 mm for super alloy under same loading conditions. To avoid the failure of a gas turbine blade due to creep, the elongation of the blade should be as less as possible. Under the same loading condition, deformation is for titanium alloy and it is almost same for Nimonic 80 A and super alloy.
Maximum stresses are observed near to the root of the turbine blade and upper surface along the blade roots. The stresses induced in the turbine blade made up of super alloy under examination and Nimonic 80 is well within the safe limits.
From the above results, it might be concluded that the super alloy which is being used for manufacture of turbine blade of marine gas turbine engine as the best suitable material.

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