Structural and Thermal Analysis of Turbine of the Engine of the Commercial Airliner

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Abstract

A **turbine blade** is the individual component which makes up the turbine section of a gas turbine. The blades are responsible for extracting energy from the high temperature, high pressure gas produced by the combustor. The turbine blades are often the limiting component of gas turbines. To survive in this difficult environment, turbine blades often use exotic materials like super alloys and many different methods of cooling, such as internal air channels, boundary layer cooling, and thermal barrier coatings. Blade fatigue is a major source of failure in steam turbines and gas turbines. Fatigue is caused by the stress induced by vibration and resonance within the operating range of machinery.

The objective of the research work is to perform Structural and Thermal analyses of the Turbine **with two configurations** to investigate which material is suitable for any one of the configuration. The first setup of the blade is the most commonly available, i.e., it is without a shroud, and the other setup is having a shroud on the rotor blades**.** Basically a shroud is a type of turbine blade with a T-shaped tip. The tips of the blades touch each other to form a ring around the turbine wheel to support the blades. Our intention is to perform analysis of the turbine with and without shroud, comparing both of these models based on the loads, we will know which design is suitable, we believe the shroud will add an advantage in reducing the structural deformations of the blade due to continuous absorption of pressure load from the oncoming combustion gases.

We will try to investigate which material is suitable to with stand the fatigue induced, by comparing the stresses, deformations and strains on the turbine blade. We will try to conclude by sighting the best material which protect blades from these high dynamic stresses. A key limiting factor in early jet engines was the performance of the materials available for the hot section (combustor and turbine) of the engine. The need for better materials spurred much research in the field of alloys and manufacturing techniques, and that research resulted in a long list of new materials and methods that make modern gas turbines possible.

Keywords: Turbine, Aircraft Engine, Thermal Analysis, Structural Analysis, Creo, ANSYS

1. Introduction

A **gas turbine**, also called a **combustion turbine**, is a type of internal combustion engine. It has an upstream rotating compressor coupled to a downstream turbine, and a combustion chamber or area, called a combustor, in between.

The basic operation of the gas turbine is similar to that of the steam power plant except that the working fluid is air instead of water. Fresh atmospheric air flows through a compressor that brings it to higher pressure. Energy is then added by spraying fuel into the air and igniting it so the combustion generates a high-temperature flow. This high-temperature high-pressure gas enters a turbine, where it expands down to the exhaust pressure, producing a shaft work output in the process. The turbine shaft work is used to drive the compressor and other devices such as an electric generator that may be coupled to the shaft. The energy that is not used for shaft work comes out in the exhaust gases, so these have either a high temperature or a high velocity. The purpose of the gas turbine determines the design so that the most desirable energy form is maximized. Gas turbines are used to power aircraft, trains, ships, electrical generators, pumps, gas compressors and tanks.

A **turbine blade** is the individual component which makes up the turbine section of a gas turbine or steam turbine. The blades are responsible for extracting energy from the high temperature, high pressure gas produced by the combustor. The turbine blades are often the limiting component of gas turbines. [10] To survive in this difficult environment, turbine blades often use exotic materials like super alloys and many different methods of cooling, such as internal air channels, boundary layer cooling, and thermal barrier coatings. Blade fatigue is a major source of failure in steam turbines and gas turbines. Fatigue is caused by the stress induced by vibration and resonance within the operating range of machinery. To protect blades from these high dynamic stresses, friction dampers are used.

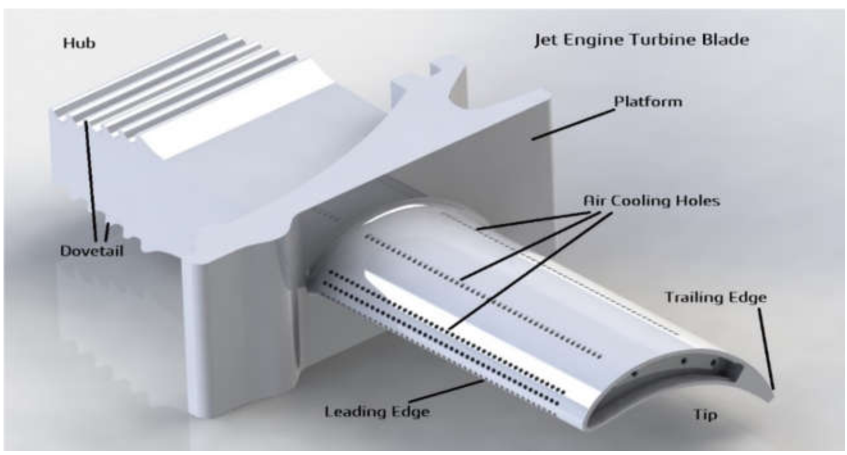

Figure 1. Turbine Blade of a Jet Engine

Turbine blades are subjected to very strenuous environments inside a gas turbine. They face high temperatures, high stresses, and a potential environment of high vibration. All three of these factors can lead to blade failures, potentially destroying the engine, therefore turbine blades are carefully designed to resist these conditions.

Turbine blades are subjected to stress from centrifugal force (turbine stages can rotate at tens of thousands of revolutions per minute (RPM)) and fluid forces that can cause fracture, yielding, or creep failures. Additionally, the first stage (the stage directly following the combustor) of a modern turbine faces temperatures around 2,500 °F (1,370 °C), up from temperatures around 1,500 °F (820 °C) in early gas turbines.

Modern military jet engines, like the Snecma M88, can see turbine temperatures of 2,900 °F (1,590 °C). Those high temperatures weaken the blades and make them more susceptible to creep failures. The high temperatures can also make the blades susceptible to corrosion failures. Finally, vibrations from the engine and the turbine itself cause fatigue failures.

2. Modelling of the Turbine Setup

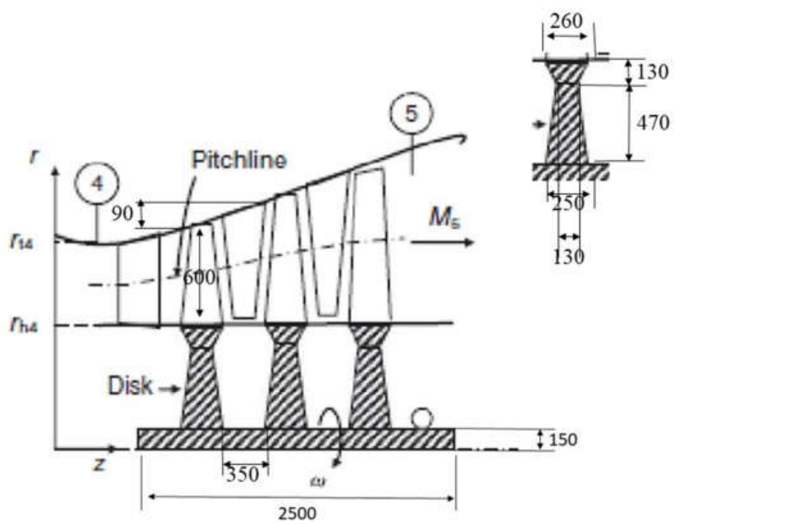

Figure 2. Reference Image for the modelling of the turbine stator-rotor setup

The dimensions of the reference image are noted and the modelling of the turbine setup is initiated, the turbine is a conventional aircraft engine axial flow turbine, which is having a multi stage turbine, having three set of Stator-Rotor setup. The Stator is fixed blade, while the rotor is the rotating blade. The stator will act as a nozzle hence increasing the velocity of air passing to the rotor. The hot air squeezes out its kinetic energy and pressure energy into the generation of torque on the shaft upon which the blades are mounted. This loss of energy is overcome by increasing its velocity in the oncoming stator of next stage. Thus we may observe that there is a loss of pressure energy across the turbine, which indicates us that the pressure is dropping across the turbine and the volume of the air is increasing hence we have an increment in the cross sectional area of the turbine downstream. The figure in the next page represents the Pressure-Velocity Diagram of a reaction turbine i.e., the axial flow turbine.

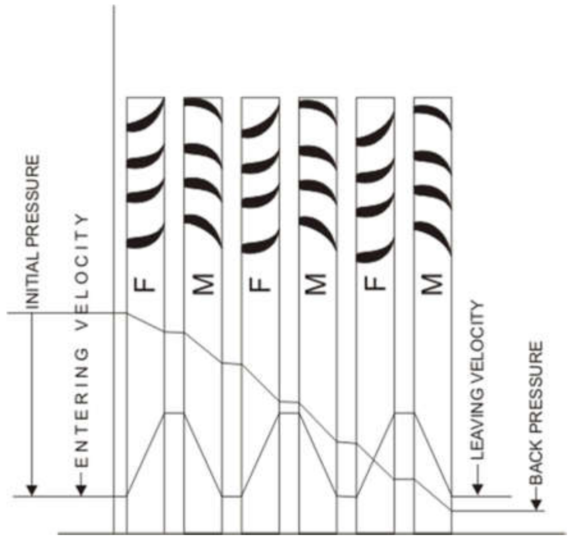

Figure 3. Pressure-Velocity Diagram of an axial flow multistage turbine

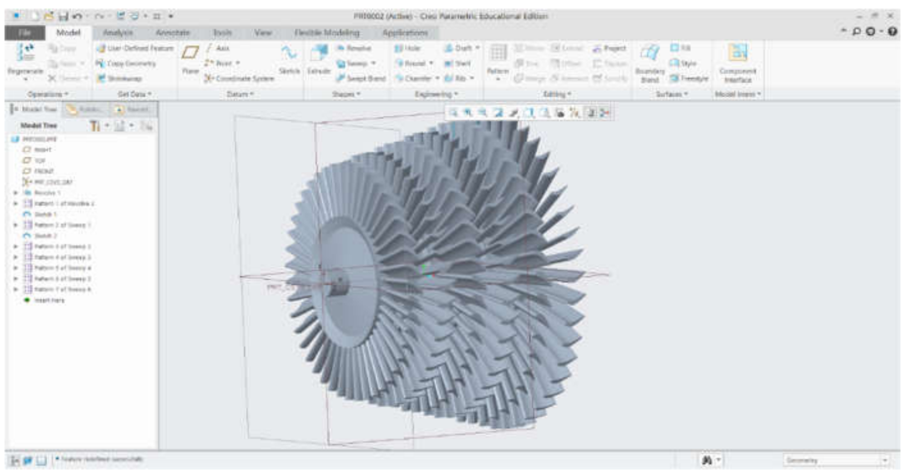

Figure 4. Final CAD Geometry of the axial flow turbine.

The above file is saved in a specific format named "Stp" format, which can be exported into ANSYS-Workbench Fluent for further analysis. Let us summon up what is the objective of the research work.

The objective of the research work is to perform Structural and Thermal analysis of the Turbine ***with two design configurations*** to investigate which material is suitable for any one of the configuration. The modelling what we have performed till now is a type of Design configuration which has **NO SHROUD.** Basically a shroud is a type of turbine blade with a T-shaped tip. The tips of the blades touch each other to form a ring around the turbine wheel to support the blades.

Our intention is to perform analysis of the turbine with and without shroud, comparing both of these models based on the loads, we will know which design is suitable, we believe the shroud will add an advantage in reducing the structural deformations of the blade due to continuous absorption of pressure load from the oncoming combustion gases.

Hence, at this point in our research work, we need to add a shroud (ring) over the end of the blade for the existing modelled geometry and save it as another file for performing analysis.

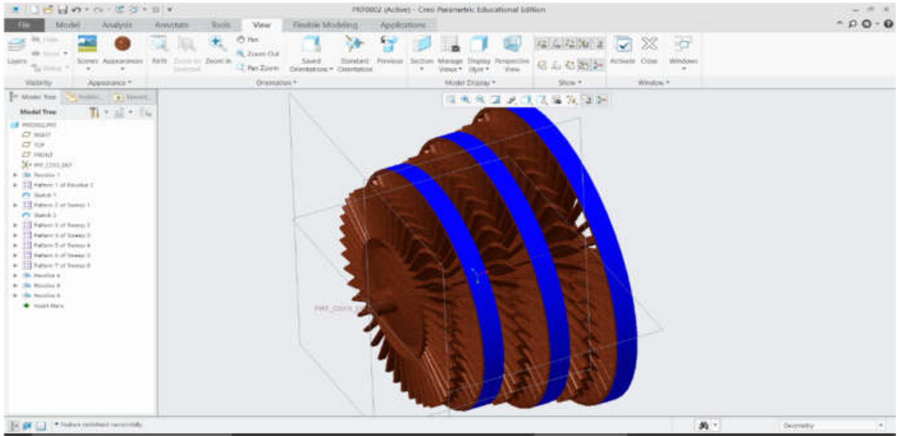

Figure 5. Final Geometry with Shroud

The above geometry is the final geometry with shroud on the rotor blades which is latter saved in STP format, this shrouded geometry and the unshrouded geometry will be performing analysis on certain common boundary conditions.

3. Structural analysis of the Turbine without Shroud

A key limiting factor in early jet engines was the performance of the materials available for the hot section (combustor and turbine) of the engine. The prerequisite for improved materials urged much research in the field of alloys and manufacturing techniques, and that research ensued in a long list of new materials and methods that make modern gas turbines possible.

Basically we should consider the material which should sustain higher temperature, apart from sustaining the pressure and velocity loads as can be seen in the reference image of the fig 4.6, which indicate the amount of loads acting on it. Hence firstly we need to select the material which can sustain huge thermal loads, as this is the major criteria, for selection of turbine blade material. The materials with higher amount of melting temperature are required. Secondly the material should also sustain the pressure of the oncoming flow, because the structural failure causes instability in functioning of the turbine, Ceramic matrix composites (CMC), where fibers are embedded in a ceramic matrix, are being developed for use in turbine blades. The main advantage of CMCs over conventional super alloys is their light weight and high temperature capability. SiC/SiC composites consisting of silicon matrix reinforced by silicon carbide fibers have been shown to withstand operating temperatures 200°-300 °F higher than nickel super alloys. GE Aviation successfully demonstrated the use of such SiC/SiC composite blades for the low-pressure turbine of its F414 jet engine.

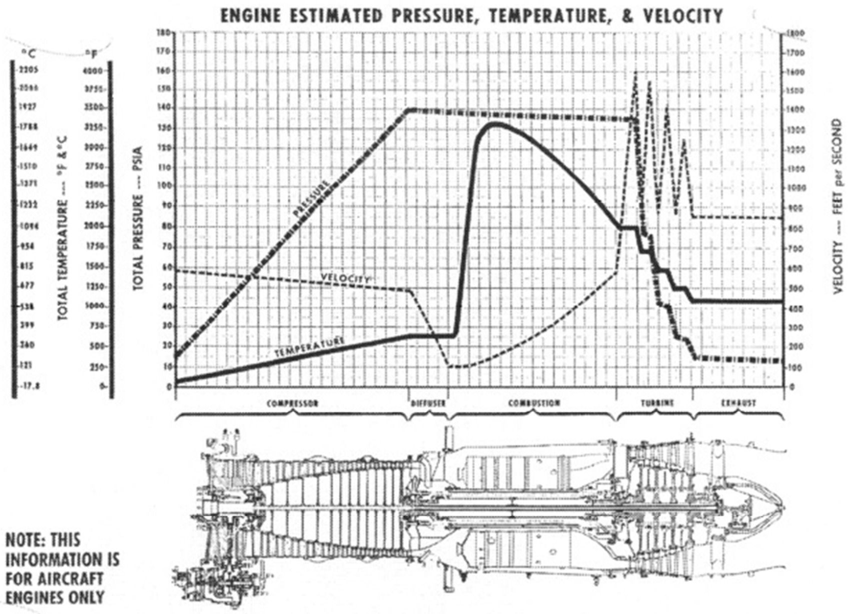

Figure 6. Pressure, Temperature and Velocity of a Gas Turbine Engine taken from "Fundamentals of Gas Turbine"

After analyzing the above figure representing the Pressure, Temperature and Velocity of Gas Turbine engine, we may see the following conditions acting on the turbine

- The Magnitude of Velocity acting = 1600 feet/sec
- The Magnitude of Pressure acting = 140 psi
- The Magnitude of temperature acting = 2000 degrees Fahrenheit.

After loads applied we change the material to Titanium Alloy and solution is done. The figures below show the Results to loads applied.

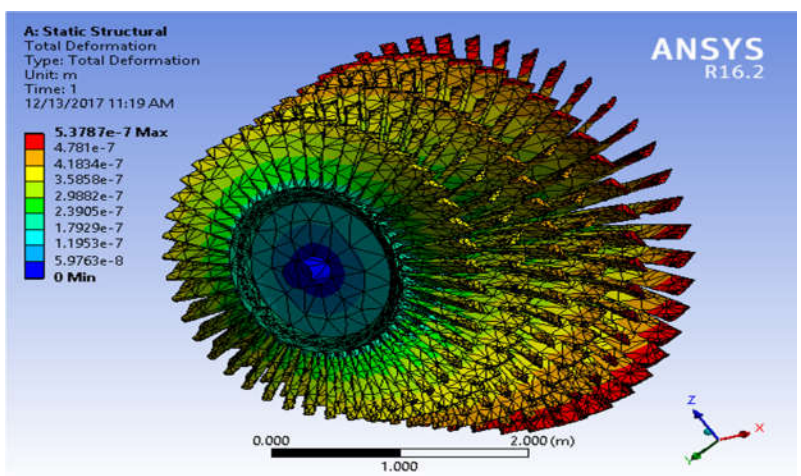

Figure 7 Total deformation of Titanium Alloy

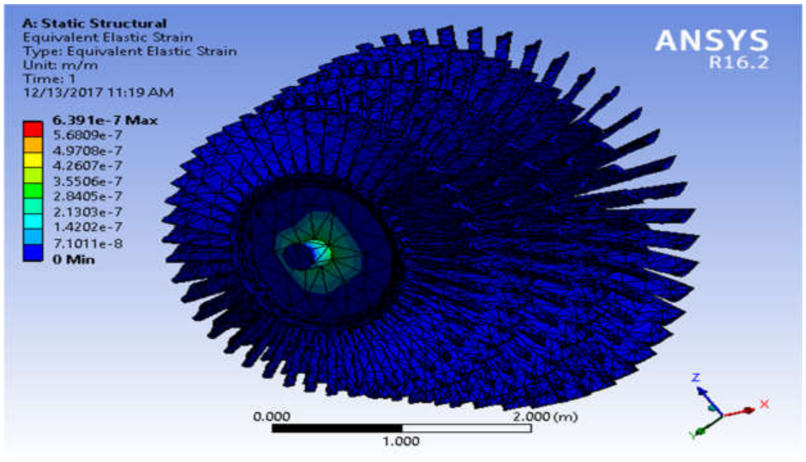

Figure 8. Equivalent Elastic Strain of Titanium Alloy

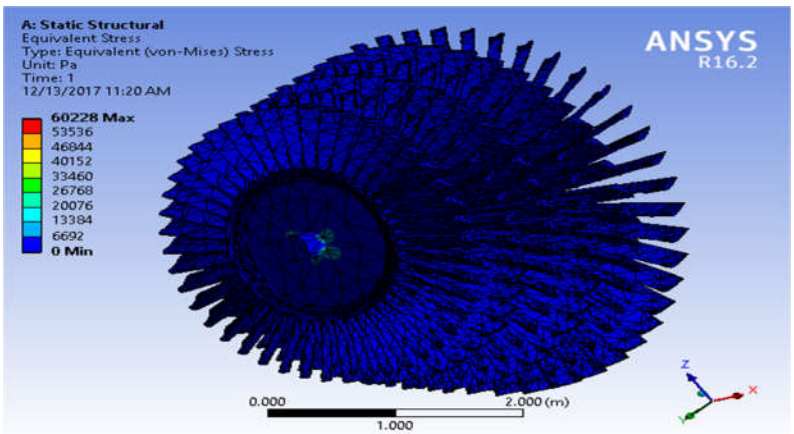

Figure 9. Equivalent stress of Titanium Alloy

After loads applied we change the material to Nickel Alloy and solution is done. The figures below show the Results to loads applied.

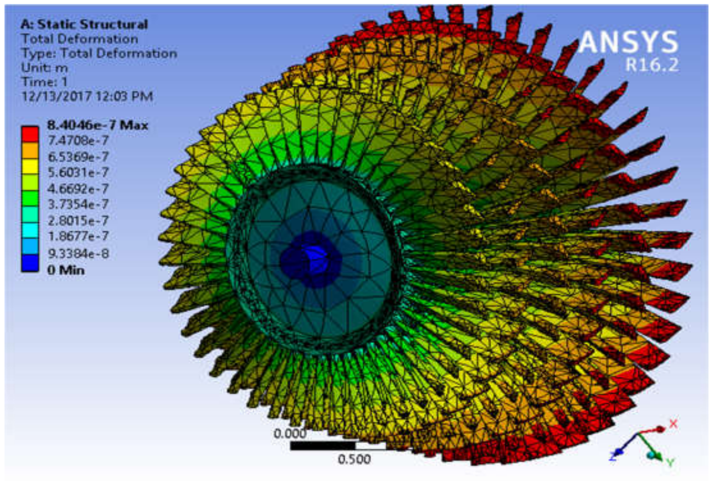

Figure 10. Total deformation of Nickel Alloy-Nimonic

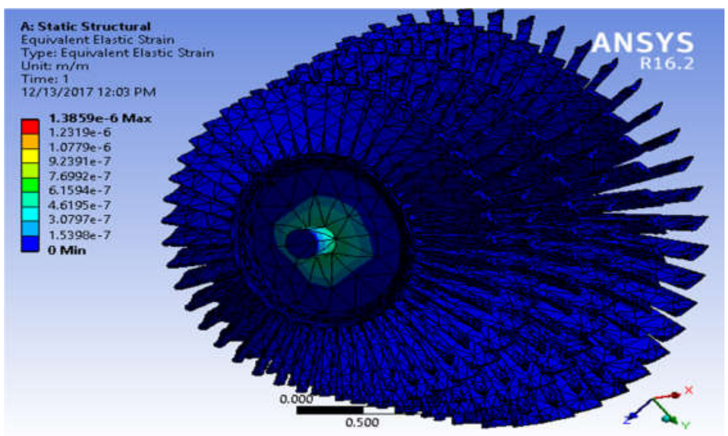

Figure 11. Equivalent elastic strain of Nickel Alloy-Nimonic

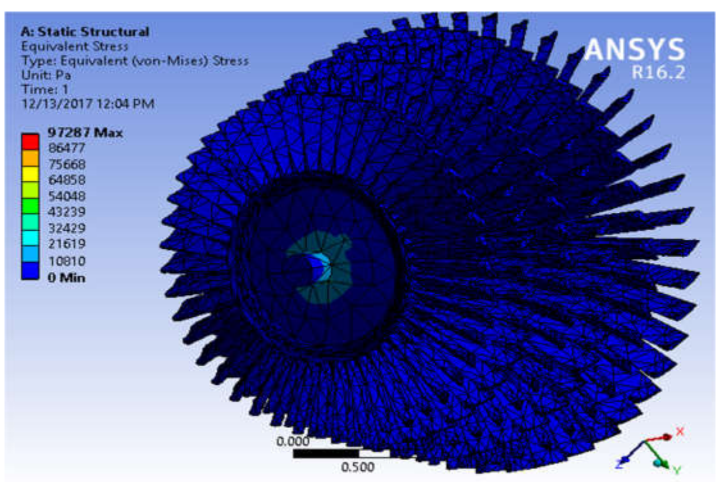

Figure 12. Equivalent stress of Nickel Alloy-Nimonic

After loads applied we change the material to Ceramic and solution is done. The figures below show the Results to loads applied.

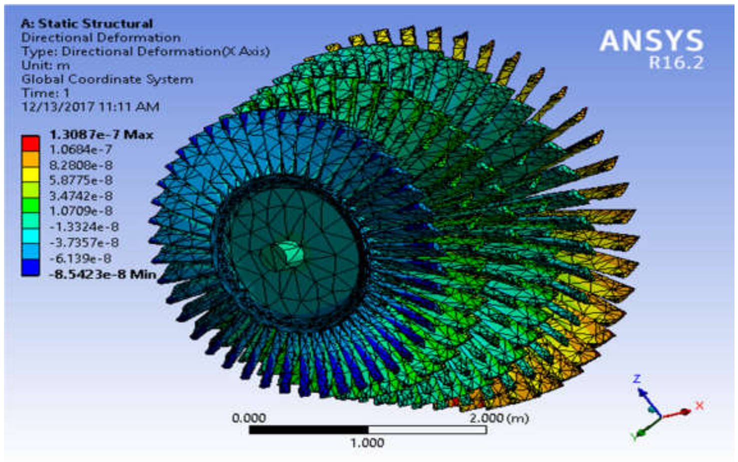

Figure 13. Total Deformation of Ceramic

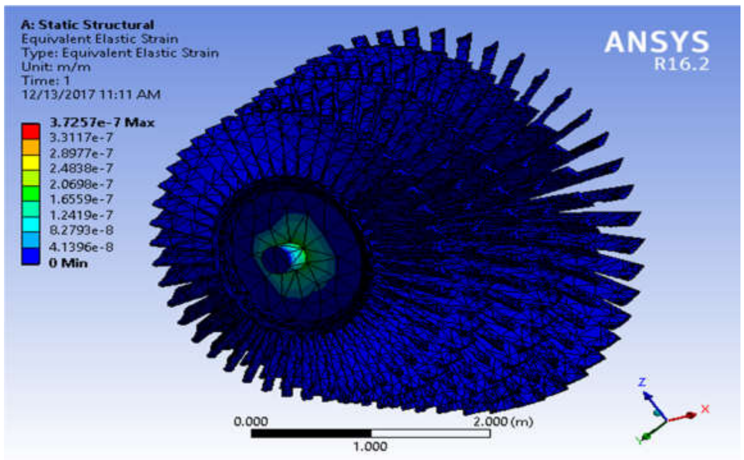

Figure 14. Equivalent elastic strain of Ceramic

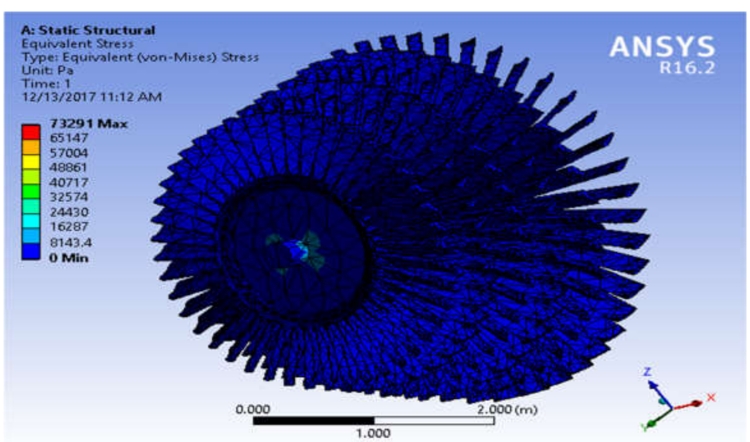

Figure 15. Equivalent stress of Ceramic

4. Structural analysis of the Turbine with Shroud

After loads applied we change the material to Titanium Alloy and solution is done. The figures below show the Results to loads applied.

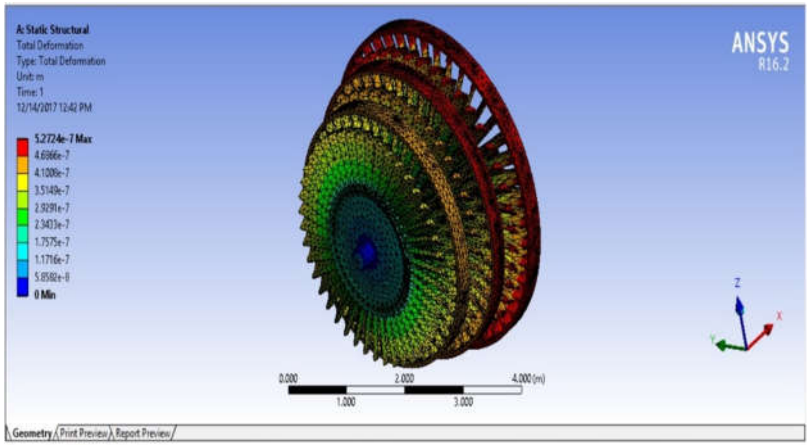

Figure 16. Total deformation of Titanium Alloy

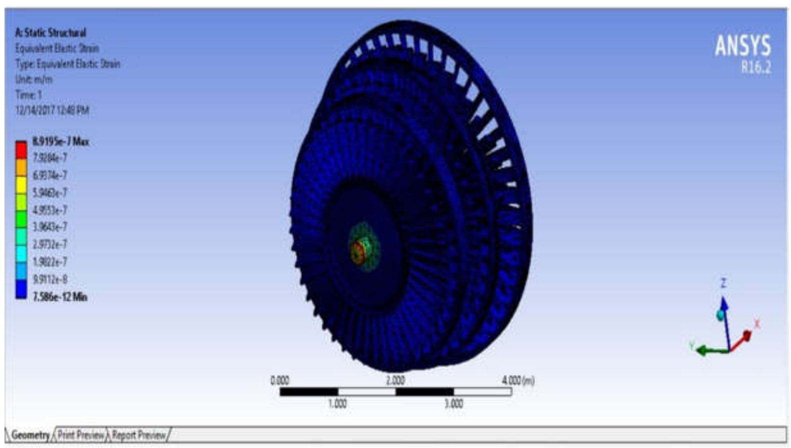

Figure 17. Equivalent Elastic Strain of Titanium Alloy

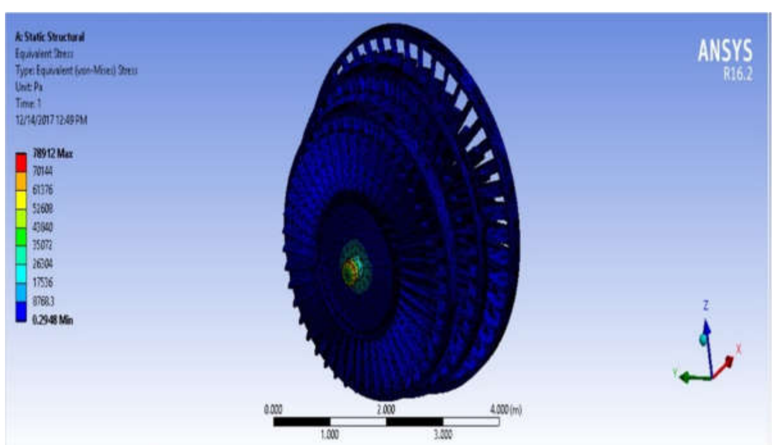

Figure 18. Equivalent stress of Titanium Alloy

After loads applied we change the material to Nickel Alloy-Nimonic and solution is done. The figures below show the Results to loads applied.

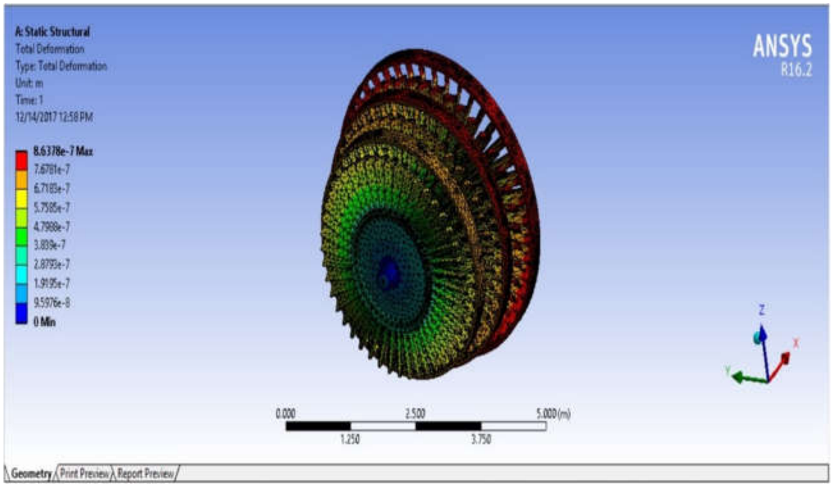

Figure 19. Total deformation of Nickel Alloy-Nimonic

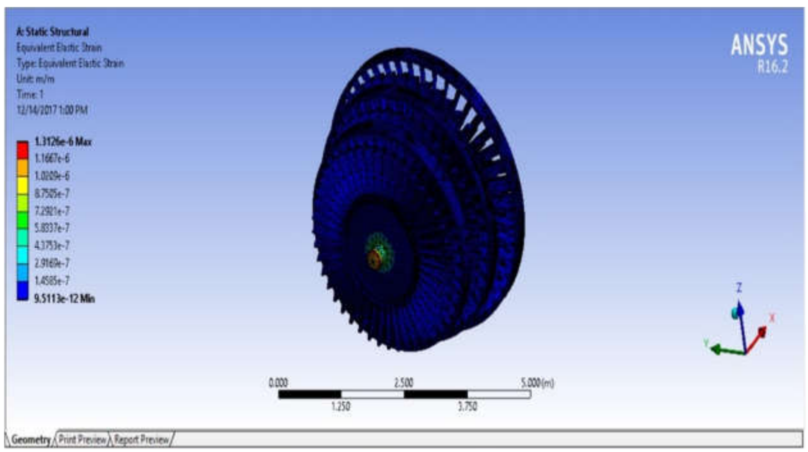

Figure 20. Equivalent elastic strain of Nickel Alloy-Nimonic

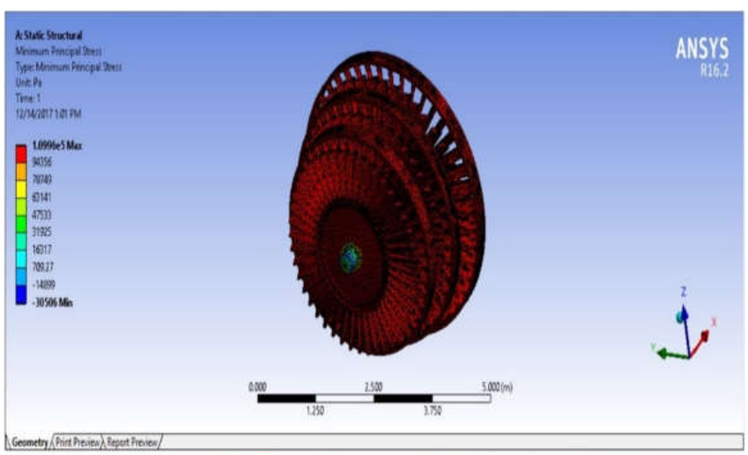

Figure 21. Maximum principal stress of Nickel Alloy-Nimonic

After loads applied we change the material to Ceramic and solution is done. The figures below show the Results to loads applied.

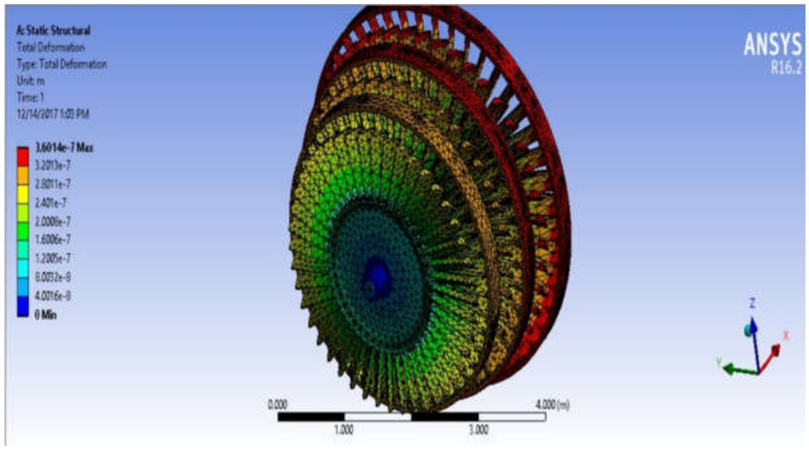

Figure 22. Total deformation of Ceramic

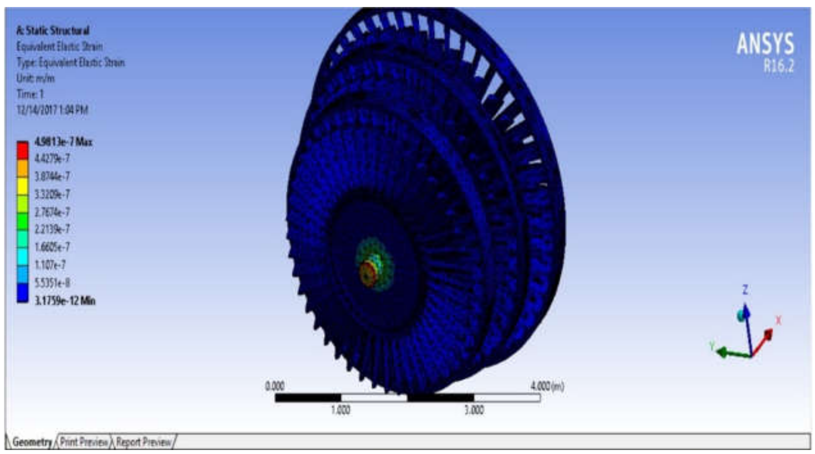

Figure 23. Equivalent elastic strain of Ceramic

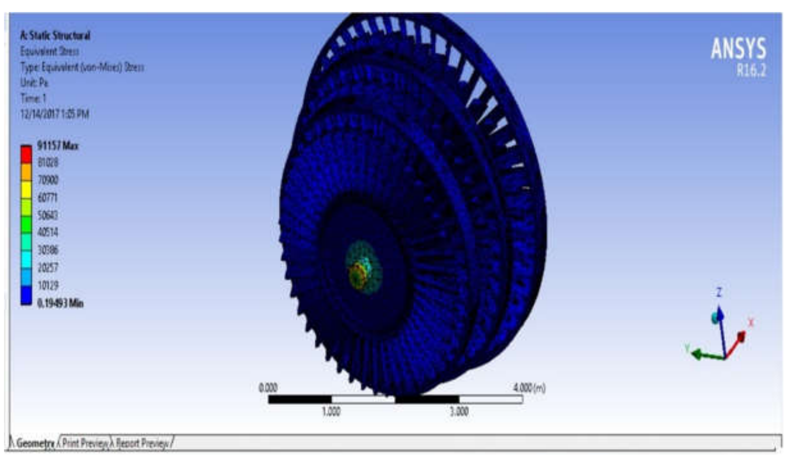

Figure 24. Equivalent stress of Ceramic

5. Thermal Analysis of the turbine with and without shroud

After meshing we need to apply loads as we are performing Thermal analysis on Turbine so we need to consider thermal loads. He we only a radiation applied on total turbine and do the analysis by varying the skin material. As we have considered three new materials we have created using different metal properties combinations and test for best results. After applying the loads select the material used and then using solve to analysis is done. Later results of each material are shown in below figures.

- Setup→ Double click→ apply →Radiation → select Geometry all→ 1000c→ apply
- Solve→ insert→ Direction heat flux →solve → ok.

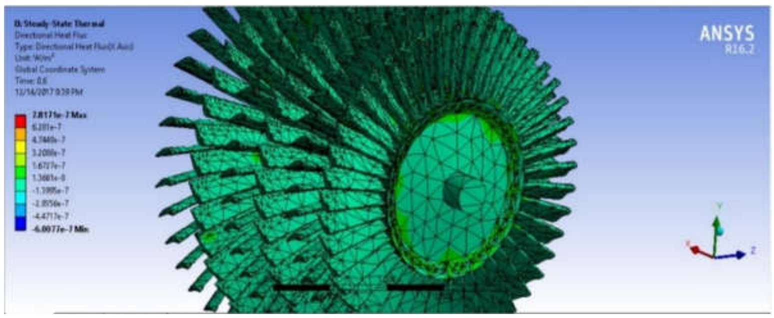

Figure 25. Directional heat flux of Turbine blades without Shroud using Nickel alloy

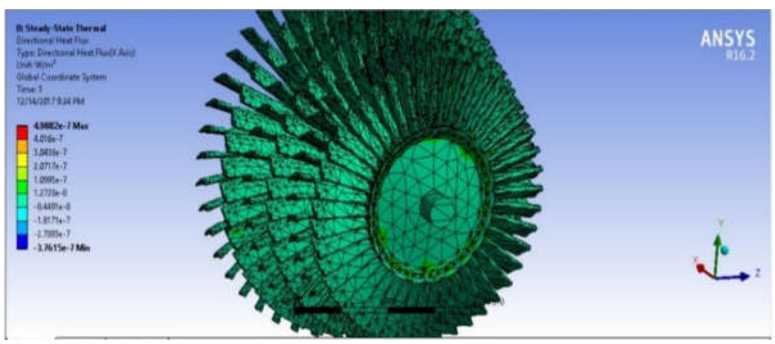

Figure 26. Directional heat flux of Turbine blades without Shroud using ceramic

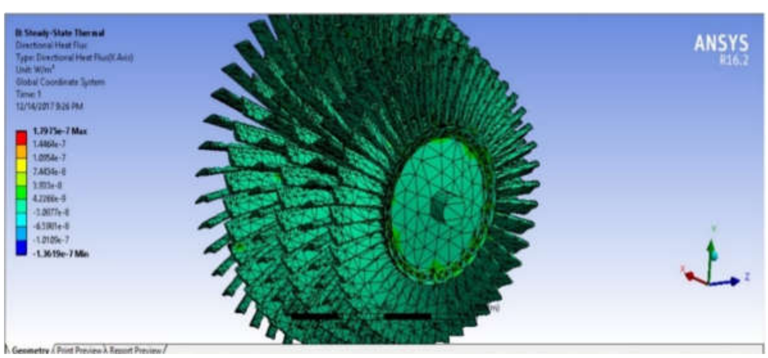

Figure 27. Directional heat flux of Turbine blades without Shroud using Titanium

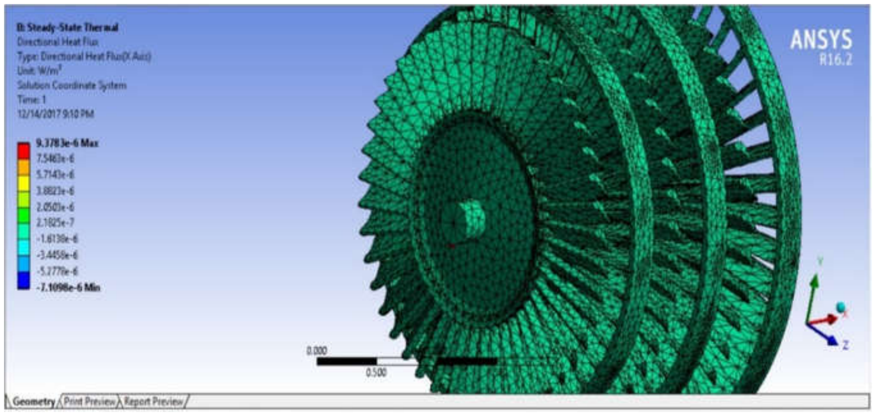

Figure 28. Directional heat flux of Turbine blades with Shroud using Nickel alloy

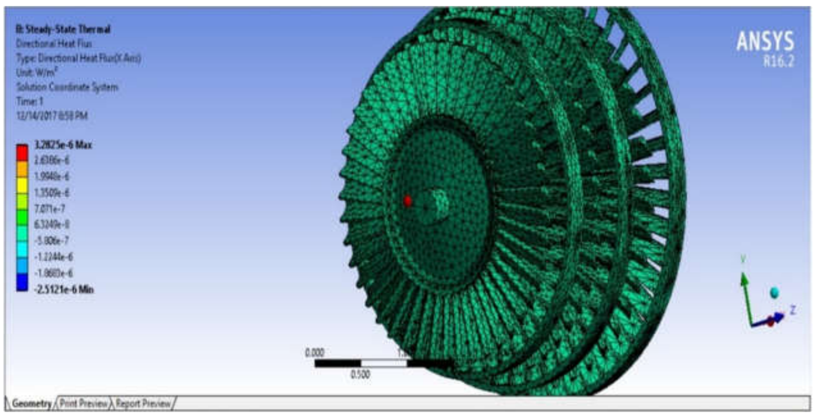

Figure 29. Directional heat flux of Turbine blades with Shroud using ceramic

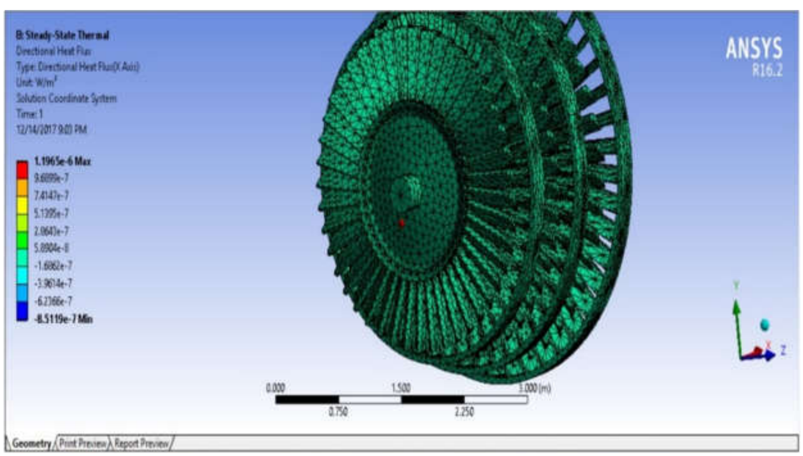

Figure 30. Directional heat flux of Turbine blades with Shroud using Titanium

6. Conclusion and Future scope

The Axial Flow Turbine of a Conventional Transport Aircraft has been modelled in Creo-4.0. Considering the "Turbine image from the Supersonic Turbine of moving Blade and Axial-Flow Turbine" we have selected the dimension as our reference and modelled the scaled geometry. After the modelling of the conventional model we have saved it in STP format and continued the modelling, i.e., we have added a shroud at each rotor of this turbine, saved the file, and then we have performed the analysis on the aircraft turbine. The objective of the research work is to find the feasibility of the shroud in reducing the stress, strain and the deformation induced in the material when it is under operation, in order to come at the conclusion we should analyze the values of Stress, Strains and Deformations that are sighted in the Results chapter.

The Structural analysis is performed on three materials that are Nickel Alloy, Titanium Alloy, and Ceramic. On Analysis of the tabulated results we may understand that the shroud is capable of reducing the deformations in the turbine, there is an ample amount of reduction is stress and strains induced which are acting on a material. Firstly as we compared the Von-Mises stress induced the Nickel material of the shrouded turbine has the less magnitude of the stress induced, which firstly sights that the shrouded configuration is on upper hand on comparison with the non-shroud turbine, and Nickel is the best suited material, Earlier to it when we analyzed the variations of deformations, we may see that the titanium material of the shrouded setup scales at better position, Once again sighting the shrouded configuration better on comparison with the shroud-less setup.

Further analysis of the magnitudes of normal stress i.e. the maximum principal stress we may see that the nickel alloy of the shrouded turbine setup has the lesser magnitudes of normal stress development, which once again bring to the point that the Nickel alloy and the shrouded setup comes first. In addition to the principal stress, the elastic strain and the principal elastic strain acting on the turbine with different materials specified us that the nickel alloy in the shrouded turbine setup has lesser distortion in the internal crystal lattice of the material. The lesser strain acting on the material is the most required strength factor for the material selection for the engineers, as the increment in strain indicates risen in the factors of failures.

On performing the thermal analysis on the three materials and checking their respective Directional Heat flux in the we can predict the materials with shroud have a lower rate of heat flow, from the tables we may observe that Ceramic and the Titanium alloy when they have Shroud attached to them, and It is to consider the fact that we require a material which has less amount of heat transfer transversely. Therefore on comparison of the two configurations and three materials, we conclude that the shrouded configuration optimum, and among the three materials in shrouded configuration the Nickel alloy is best material, which has the less rate of heat transfer. We may conclude that the shrouded configuration is the finest in terms of the heat transfer rate.

Although we need to compromise on various factors, based on the application of the aircraft. In this research work we are considering the deformation, equivalent stress & equivalent strain and Directional heat Flux as the factors for material selection. Neglecting the availability, cost, weight, Nickel Alloy is well suited if we consider all the above major factor in material selection. As can be seen from the results that the Nickel Alloy has less deformation and less Stress acting on it with Shroud. Therefore we conclude that the best suited material for the Axial Flow Turbine of a Conventional Transport Aircraft is Nickel alloy. And the Configuration of the turbine with the Shroud is the optimized one.

The research work sites the importance and implication of shrouds on the rotor blade tips and we suggest that upon the usage of shroud at the ends of rotor blade of a turbine, an improved distinction can be attained in various parameters of structural fitness like Deformations on the Turbine Blades, Stresses and Strains induced on the Turbine Blades. Apart from sighting the importance and implication of shroud at the rotor blade assemblies, we have also suggested the best suited material for the turbine setup which when is acted by the specific boundary conditions will sustain the loads in an evener fashion.

Turbines are manufactured by investing huge amount of money, and are expected to function for a number of years, and during the operation there are many chances of structural failures which are being are under research by many research firms, who try to minimize the failure by varying the current configurations either in design or material standpoint. We have done a similar research work which propose an optimized configuration of the turbine setup with the nickel alloy as the suited material.

Reference

[1]. Introduction to Engineering Thermodynamics, Richard E. Sonntag, Claus Borrgnakke 2007. Retrieved 2013-03-13

[2]. "CFD for Aero Engines" (PDF). HCL Technologies. April 2011. Retrieved 2016-03-13

[3]. "Ceramic Matrix Composites Allow GE Jet Engines to Fly Longer - GE Reports". GE Reports. Retrieved 2015-11-02.

[4]. V.Raga Deepu, R.P.Kumar Ropichrla. "DESIGN AND COUPLED FIELD ANALYSIS OF FIRST STAGE GAS TURBINE ROTOR BLADES", International journal of Mathematics and Engineering, Vol 13, No.2, Pages: 1603-1612

[5]. https://www.aircraftmaterials.com/data/nickel/nimonic90.html

[6]. "Fundamentals of Gas Turbine Engine"- http://www.castsafety.org/pdf/3_engine_fundamentals.pdf

[7]. http://ceramics.org/learn-about-ceramics/ceramic-engineering-in-aerospace ceramic link

[8]. REVIEW OF STRUCTURAL AND THERMAL ANALYSIS OF GAS TURBINE BLADE, International Journal of Mechanical Engineering and Robotics Research, Vol. 3, No. 2, April 201

[9]. Introduction to Engineering Thermodynamics, Richard E. Sonntag, Claus Borrgnakke 2007. Retrieved 2013-03-13