Comparative Structural and Thermal Analysis of Aircraft Turbojet Gas Turbine Blade using Finite Element Analysis and Formulation

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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. In modern Aviation systems, turbine blades are made up of nickel based super alloys, generally N155 and Inconel alloys. Three widely used alloys namely N155, MAR M246 and Nimonic 80A are being selected for virtually constructing the blade and analysis purpose after going through several research works in relevant field. The present work is concerned with determining the best suited alloy among the three selected alloys mentioned above under a set of working parameters. An individual turbine blade has been modelled using SOLIDWORKS 2016. All the three materials are being virtually generated and the analysis work is carried out in the Finite Element Analysis software ANSYS Workbench V14.0. The results obtained from the analysis had been used to determine the total deformation, Von mises stress, Von mises strain and heat flux for each material under variable force and constant turbine inlet temperature. It is observed from the analysis that N155 has been found to exhibit better suitability and characteristics.

Keywords: Gas Turbine Blade; Finite Element Analysis; Nickel Alloys; Structural Analysis; Turbojet Engine.

I. INTRODUCTION

The gas turbine is an internal combustion engine that uses air as the working fluid. The engine extracts chemical energy from fuel and converts it to mechanical energy using the gaseous energy of the working fluid (air) to drive the engine and propeller, which, in turn, propel the airplane.

The basic principle of the airplane turbine engine is to extract energy from chemical fuel. The basic 4 steps for any internal combustion engine are:

1. Intake of air (and possibly fuel).
2. Compression of the air (and possibly fuel).

3. Combustion, where fuel is injected (if it was not drawn in with the intake air) and burned to convert the stored energy.
4. Expansion and exhaust, where the converted energy is put to use.

Four types of gas turbine engines are used to propel and power aircraft. They are the turbojet, turbofan, turboprop, and turboshaft. Our present work is concerned with the turbojet type of gas turbine engine (Figure 1.1).

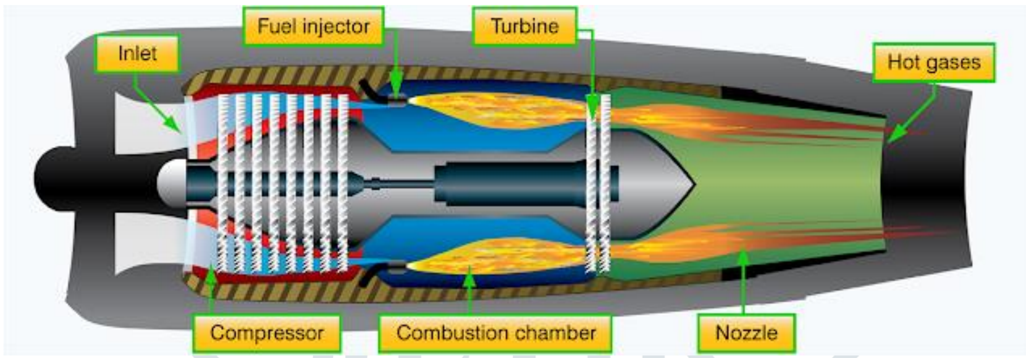

Figure 1. Schematic Diagram of a Turbojet Engine

In the present work a turbine blade has been used and analyzed for three different materials discussed in below section briefly. The aim of the work is to find out the maximum structural and stress parameters experienced by the blade under the specified set of operating conditions consists of very high temperature and variable extreme force and to choose the best material among the selected three materials. Modeling and analysis work has been performed on 3D-Modeling Software SOLIDWORKS and Finite Element Analysis software ANSYS Workbench V14.0 respectively.

A. Literature Review

The gas turbine blades in turbojet engine works under the most exhausting conditions of temperature and pressure. To enhance the properties of blades suitable material should be chosen which should have high temperature creep resistance, high thermal stability, high tensile strength, resistance towards oxidation and hot corrosion (Carter 2005, Cowles 1996, Chintala and Gudimetla 2014, Madhu P 2015, Ravindra and Raju 2017). Parameters like blade profile selection, material selection and turbine rotor blade vibration seriously impact the induced stress-deformation and structural functioning of developmental gas turbine engine (Kumar and Pandey 2017). Nickel based super alloys (Khawaja and Motamedi 2014, Gurajarapu and Rao 2014, Aabid and Khan 2018, Theju and Uday 2014, Deepanraj and Lawrence 2011) and titanium based alloys (Mazarbhuiya and Pandey 2017, Ravindra and Raju 2017) are generally used in aviation purpose and are analyzed by most of the authors. Structural analysis (Rogge and Berger 2018, Geetha S.M. 2017, Umamaheswararao and Mallikarjunarao 2014, Amoo 2012, Deepanraj and Lawrence 2011) thermal analysis (Umamaheswararao and Dr. Mallikarjunarao

2014, Gurajarapu and Rao 2014) and the effect of cooling on the blade (Deepanraj and Lawrence 2011, Prasad and Ravitej 2016) are the most common area of analysis among the authors. Structural parameter like Total Deformation, Max-Von Mises Stress and Thermal Strain (Ravindra and Raju 2017, Y. Yang and L. Yang 2015, Kumar and Rose 2015, Kumar and Pandey 2016) and thermal parameters like temperature distribution are taken under consideration. Most of the observed work shows that maximum stresses and strains are observed near to the root of the turbine blade. Temperature distribution is decreasing from the tip to the root of the blade section (Kumar and Rose 2015, Mazarbhuiya and Pandey 2017).

An appropriate coating is essential for enhancing the life of the blade. Owing to which, thermal barrier coating on the blade is adopted to reduce the temperature of the underlying substrate and also to provide protection against oxidation and hot corrosion. One of the prominent TBC for Inconel blades consists of initial coat is super alloy-INCONEL 718 with 1 mm thickness, bond coat is Nano-structured ceramic-metallic composite-NiCoCrAIY with 0.15 mm thickness and top coat is ceramic composite-La2Ce2O7 with 0.09 mm thickness on the nickel alloy turbine blade which in turn increases the strength, efficiency and life span of the blades (Sadowski and Golewski 2011, Ujede and Bhambere 2014, Aabid and Khan 2018). For low stress displacement in Inconel blades the Cast Iron with Zirconium and platinum aluminium or platinum chromium are more beneficial (Ujede and Bhambere 2014).

Apart from material study and TBCs, cooling of the blade, fatigue and failure analysis, study of microstructure and vibrational analysis were also very crucial area of work for many authors in the fields of gas turbine. A study showed that turbine blade with 8 holes configuration for cooling purpose was found to be the optimum solution (Prasad and Ravitej 2016, Deepanraj and Lawrence 2011).

II. MATERIALS AND METHOD

A. Materials Used

Three materials are used for present analysis of the aircraft turbine blade. All the materials are variants of Nickel based Superalloys namely N155, MAR M256 and Nimonic 80A. These three materials are mainly used to make turbine blades for usage in aviation.

Nimonic alloy 80A (UNS N07080/W. Nr. 2.4952 & 2.4631) is a wrought, age-hardenable nickel-chromium alloy, strengthened by additions of titanium, aluminum and carbon, developed for service at temperatures up to 815°C (1500°F). It is produced by high-frequency melting and casting in air for forms to be extruded. Electroslag refined material is used for forms to be forged. Vacuum refined versions are also available. NIMONIC alloy 80A is currently used for gas turbine components (blades, rings and discs), bolts, nuclear boiler tube supports, die casting inserts and cores, and for automobile exhaust valves.

N155 alloy (UNS R30155, W73155) is recommended for us in applications involving high stress at temperatures up to 1500°F, and moderate stress up to 2000°F. It has excellent oxidation resistance, good ductility, and is readily fabricated. Its high-temperature properties are inherent and are not dependent upon age-hardening. Production and use of the alloys dates back to the late 1940s. The alloy has been used in a number of aircraft application including tailpipes and tail cones, afterburner parts, exhaust manifolds, combustion chambers, turbine blades, buckets, and nozzles. It also gives excellent service for high-temperature bolts, and has proven to be an economical material of construction for use in heat-treating equipment where strength at high temperatures is essential.

The MAR-M246 superalloy generally solidifies with a dendritic structure containing carbides and exhibits extensive interdendritic segregation. A variant alloy, called MAR-M246 (Hf), contains 1.5 wt.% hafnium, which is added as a carbide former and grain boundary strengthener. Mar-M246 is a kind of Nickel-based casting alloy which is strengthen by the precipitation phase. It has high persistent strength and creep rupture strength at 650-1040℃which simultaneously has good anti-oxidation property and be good at casting complex shape castings as well as making a single turbo.

B. Methodology

The following methodology is carried out during the present work;

1. The literature review has been carried out to understand the steady structural and thermal analysis of turbine blade.
2. The turbine blade required for the analysis purpose has been modelled using 3D-Modelling Software SOLIDWORKS V2016.
3. After modeling of the blade, Finite Element Analysis has been carried out using ANSYS Workbench V14.0. Three different materials i.e.N155, MAR M246 and NIMONIC 80A have been selected for the purpose of analysis.
4. The analytical results of Deformation, Von-Mises Stress, Von-Mises Strain and Heat Flux are being generated using ANSYS for all the three materials.
5. Analytical validation of results from given parameter by comparing with mathematical formulation has been carried out using the numerical comparison.

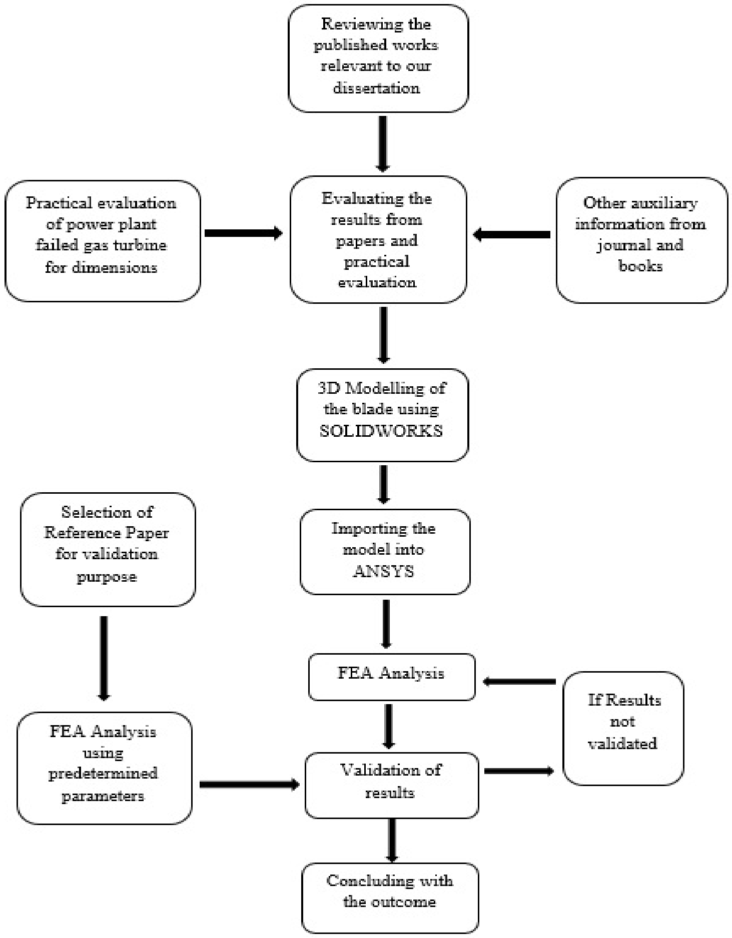

Figure 2. Procedures showing steps in Methodology. (Mullick et al. 2019).

III. RESULTS AND DISCUSSION

This section shows the Deformation, Von mises stress, Von mises strain and Heat flux variation caused in the turbine blades in all three selected materials namely N155, MAR M246 and NIMONIC 80A w.r.t time. As the time interval increases input values of force varies from 25000N to 35000N. The figures (2 to 13) are the images from the solver output of the ANSYS software which shows, how the variations in the selected output parameters occurs along the blade length and also with respect to time. The turbine inlet temperature is maintained at of 1000 ^{o}C.

Further design parameters are as follows;

1. Effective Height of the blade is 175 mm.
2. Volume of the Bounding Box is 2.525 x 10^7 mm3.
3. Volume of the Blade (Volume of bounding box–Volume of the base) is 8.36 x 10^6 mm3.
4. Effective mass of the blade is 68.578 kg.

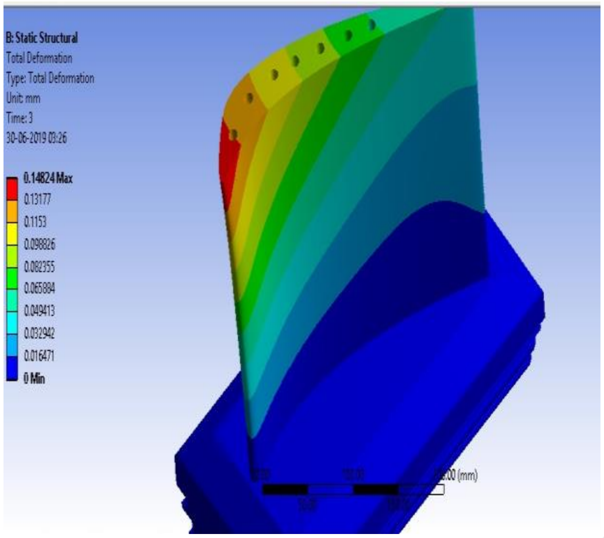

Figure 3. Deformation of N155 of turbine blade.

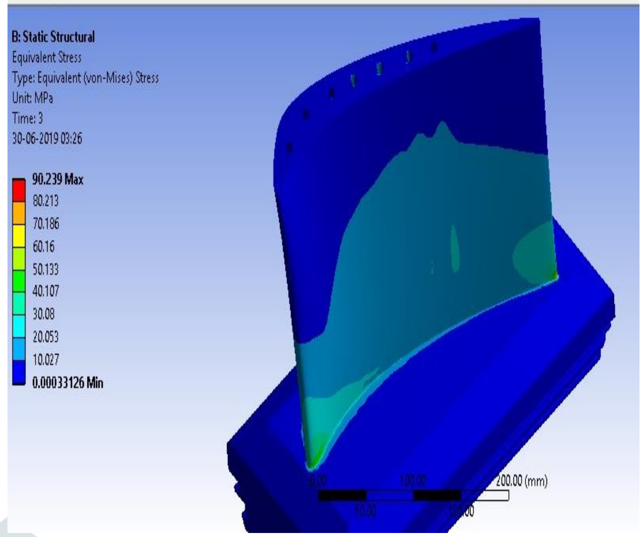

Figure 4. Von mises Stress distribution in N155 Turbine Blade.

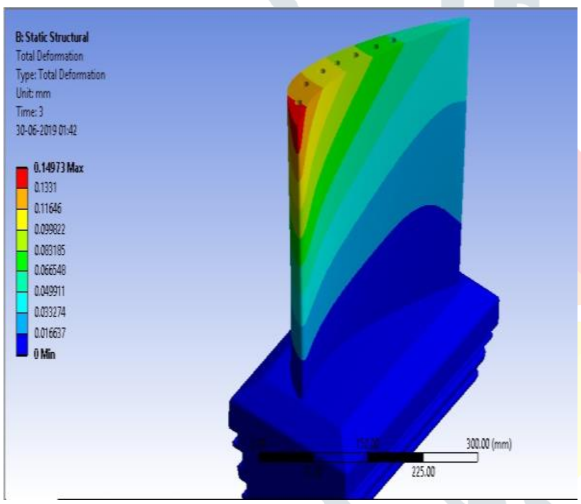

Figure 5. Deformation of MAR M246 of turbine blade.

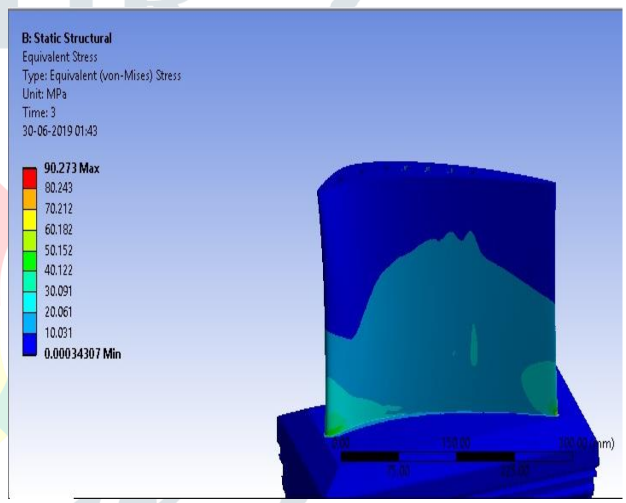

Figure 6. Von mises Stress distribution in MAR M246 Turbine Blade

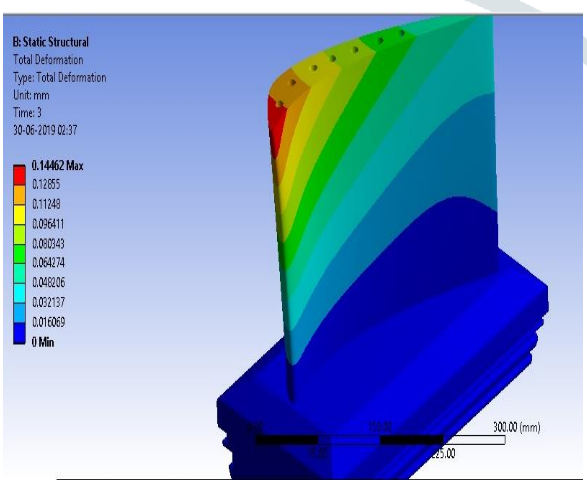

Figure 7. Deformation of NIMONIC 80A of turbine blade.

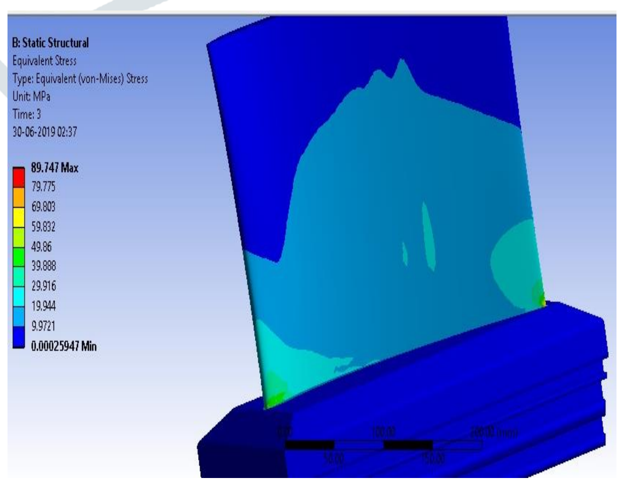

Figure 8. Von mises Stress distribution in NIMONIC 80A Turbine Blade.

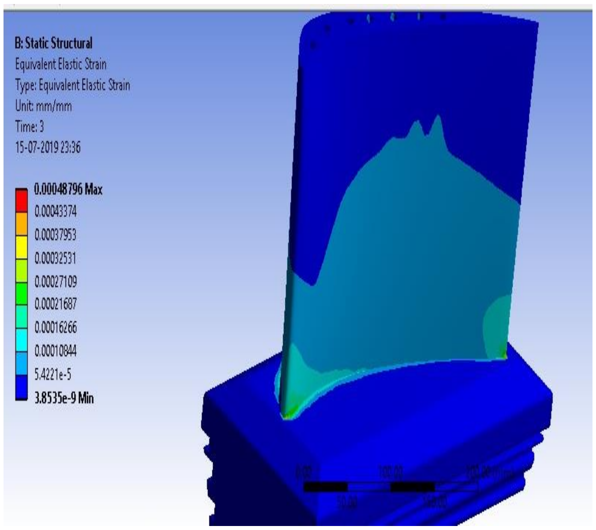

Figure 9. Von mises Strain distribution in N155 Blade.

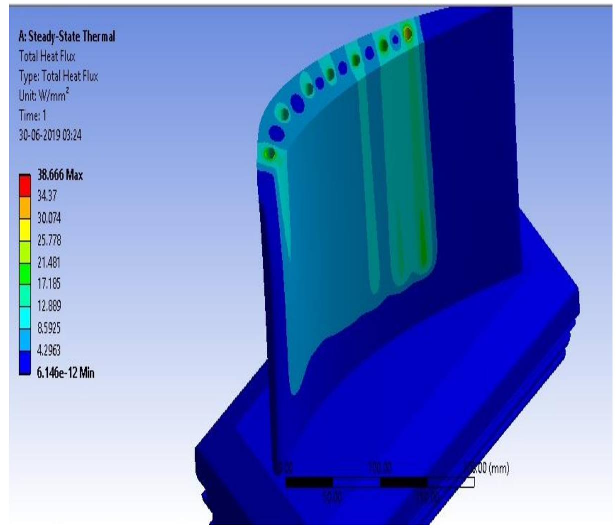

Figure 10. Heat flux distribution in N155 Turbine Blade.

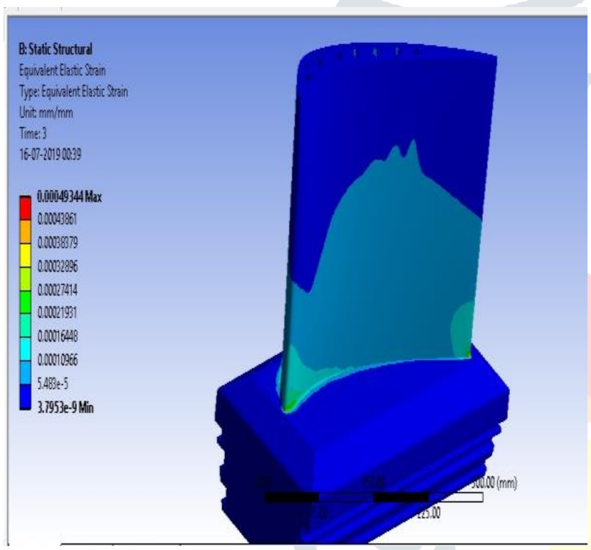

Figure 11. Von mises Strain distribution in MAR M246 Blade.

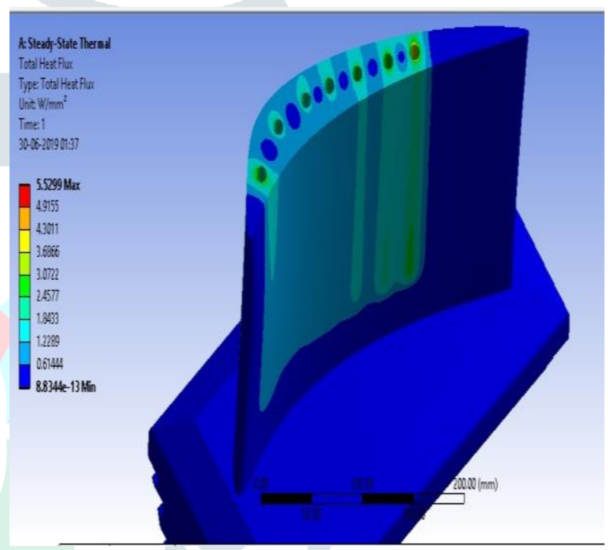

Figure 12. Heat flux distribution in MAR M246 Turbine Blade.

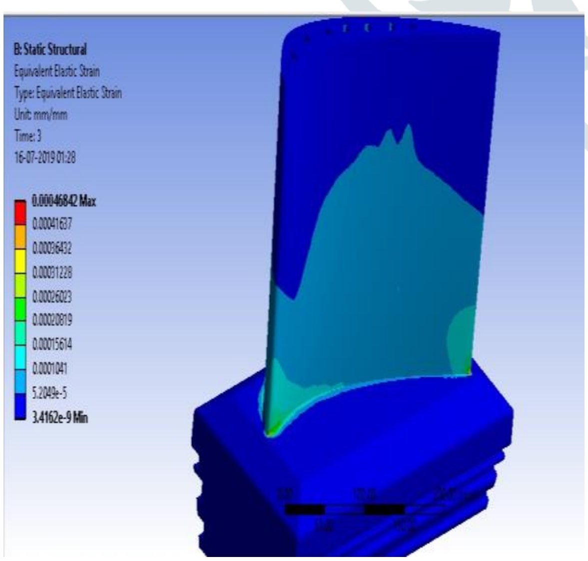

Figure 13. Von mises Strain distribution in NIMONIC 80A Blade.

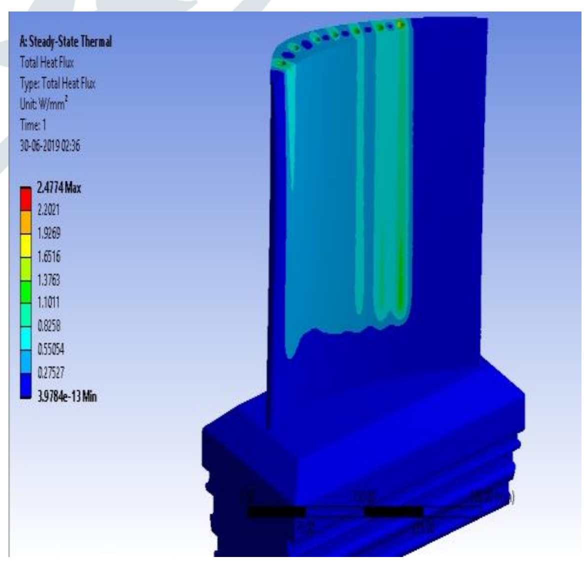

Figure 14. Heat flux distribution in N155 Turbine Blade.

It is observed from the Figures 3, 5 and 7 that the blade deforms as the constraints in movement decreases gradually which leads to deform the blade maximum at the tip of the blade and least in the root. At the peak load of 35000N the maximum deformation observed in N155 is 0.14824 mm, 0.14973 mm in MAR M246 and 0.14462 mm in NIMONIC 80A. N155 shows the least deformation among the three materials so considered to be better in the category of deformation.

It is observed from the Figures 4, 6 and 8 related to Von mises stress, at the peak load of 35000N the Von mises stress in N155 is 90.239 MPa, 90.273 MPa in MAR M246 and 89.747 MPa in NIMONIC 80A. All the stress values are under the limit of maximum allowable stress and maximum tensile yield strength indicting that the blades are not yet fractured. The outcome shows that the N155 shows the least stress accumulation among all three. But it is also evident that the other two doesn’t lag in stress values significantly.

It is observed from the figures 9, 11 and 13 that at the peak load of 35000N the value of the Von mises Strain is 4.8796 x 10^{-4} mm/mm in N155, 4.9344 x 10^{-4} mm/mm in MAR M246 and 4.6842 × 10^{-4} mm/mm in NIMONIC 80A. The results shows that the NIMONIC 80A shows the least strain among all three. The Von mises Strain shows almost similar demographics as the Von mises Stress parameter. The measure and degree of strain is least in blue region and highest in the red coloured region. The blade root is directly attached to the rotating rim of the turbine which constrains the measure of deformation which in turn produces comparatively more strain at the root.

It is observed from figures 10, 12 and 14 that at the peak load of 35000N the Heat flux is 38.666 W/mm^2 in N155, 5.5299 W/mm^2 in MAR M246 blade and 2.4774 W/mm^2 in NIMONIC 80A. The results clearly shows that the concentration of the Heat flux is least in blade made up of N155.

A. Validation of the Results

Table 1. Data of Validation for Strain for N155, MAR M246 & NIMONIC 80A

Validation data for Von mises Strain (mm/mm) (At peak load)			
	N155	**MAR M246**	**NIMONIC 80**
Ansys Generated Data	4.8796 x 10^{-4} mm/mm	4.9344 x 10^{-4} mm/mm	4.6842 × 10^{-4} mm/mm
Data from Mathematical Formulations	4.468 x 10^{-4} mm/mm	4.5139 x 10^{-4} mm/mm	4.3356 x 10^{-4} mm/mm
% Difference	8.43%	8.52%	7.44%

Table 2. Data of Validation for Deformation for N155, MAR M246 & NIMONIC 80A

Validation data for Deformation (mm) (At peak load)			
	N155	**MAR M246**	**NIMONIC 80**
Ansys Generated Data	0.14824 mm	0.14973 mm	0.14462 mm
Data from Mathematical Formulations	0.13535mm	0.13671mm	0.13209mm
% Difference	8.695%	8.59%	8.61%

As it is evident from the above tabular data that the margin of the difference is between 3-10 percent. The results are considered to be the precise and credible. The values of the similar parameters related to other materials are now also being considered validated as they generated from same software and approach.

IV. SUMMARY AND CONCLUSION

The present work focuses on the structural and thermal analysis of the turbine blade of a gas turbine used for power generation made of different Nickel based Super-alloys N155, MAR M246 and NIMONIC 80A. The four key parameters which provides the best indications about the suitability of the material taken here are Deformation, Von-Mises Strain, Von-Mises Stress and Heat flux. All the materials are designed using SOLIDWORKS and tested on the mentioned parameters using ANSYS Workbench V14.0 Software.

The concluding points are as follows:

1. N155 is considered as the best suited material among the three selected alloys under the given working conditions.
2. Although N155 is the considered as best suited one, the other two materials also yields results having very less difference.
3. It is also observed that Nimonic 80A shows least strain values out of all other materials which is because of its modular of Elasticity.
4. All the results generated here are under the safe and allowable limits.

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