Comparative Structural Analysis of the Gas Turbine Blade made up of Nickel based Super Alloys

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Abstract: In modern power generation systems, turbine blades are made up of nickel based super alloys, generally Inconel or Nimonic alloys. Three widely used Inconel alloys namely Inconel 718, Inconel 625 and Inconel 738 are being selected for virtually constructing the blade and analysis purpose after going through several research works in the relevant field. The present work is concerned with determining the best suited Inconel alloy among the three commonly used 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 have been used to determine the total deformation, Equivalent stress, Equivalent strain and strain energy for each material under variable pressure and constant turbine inlet temperature. It is observed from the analysis that Inconel 625 has been found to exhibit better suitability and characteristics.

Keywords: Gas Turbine Blade; Finite Element Analysis; Nickel Alloys; Steady-Structural Analysis; Thermal Barrier Coating.

I. INTRODUCTION

Gas turbine is a rotary type internal combustion thermal prime mover. The gas turbine plant work on a gas power cycle. Of the various means of producing mechanical power, the gas turbine is in many respects the most satisfactory one. Its outstanding advantages are:

- Exceptional reliability,
- Freedom from vibration,
- Ability to utilize grades of fuel not suitable for high performance spark-ignition engines, and;
- Ability to produce large bulk of power from units of comparatively small size and weight.

The gas turbine obtains its power by utilizing the energy of a jet of burnt gases and air, the velocity of jet being absorbed as it flows over several rings of moving, blades, which are fixed on a rotor mounted on a common shaft. It thus, resembles a steam turbine, but it is a step forward in eliminating water-to steam step (the process of converting water into steam in a boiler) and using hot gases directly to drive the turbine. The essential difference between a reciprocating internal combustion engine and a gas turbine, apart from the difference in reciprocating and rotary motion, is that in the I.C. Engine, compression, combustion and expansion take place in a single component (cylinder), while in gas turbine, each of these operations is produced in a separate components.

In the present work a turbine blade has been used and analysed 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 extreme pressure and to choose the best material among the selected three materials. Modelling and analysis work has been performed on 3D-Modelling Software SOLIDWORKS and Finite Element Analysis software ANSYS Workbench V14.0 respectively.

A. Literature Review

Modern combined cycle gas-turbine (CCGT) engines require a fundamental increase of turbine inlet temperatures (TIT) for achieving the peak efficiency. This thermodynamic trend resulted in a raised couple temperature, enhanced diffuse casualty and hot-corrosion criticize of the hotter-engine materials. In specific, the gas-turbine (GT) blades direct under the most backbreaking conditions of temperature and express of any division in the engine.

Further the design of the blade also plays a crucial part along with selecting suitable material for designing the turbine blades there are many factors that has to be taken under consideration. Nickel based Superalloys (Inconel, Nimonic, MAR-M246/247, Hastealloy) [1-5,16] and Titanium based alloys [6-7] are preferred for the designing of turbine blades Nickel-based super alloys march an excellent high-temperature creep resistance, thermal stability, very good tensile strength, micro-structure stability for high temperature and resistances to oxidation and hot corrosion. Similar traits are shown by Titanium alloys too. For these reasons, they are used in the manufacturing of gas turbine hot-section components. The potential difference between the usage of the Ni-Alloys and Ti-Alloys are concerned with area of operations. Ni-Alloys are preferred for power generation purposes whereas the Ti-Alloys are generally ideal for Aviation purposes [8]. Cobalt based Superalloy X [9] is also been considered for the turbine propellers for marine operation. Summarily it is evident that in most of the cases the Nickel based Superalloys generally have better stability, durability, mechanical and thermal properties and longevity across variable set of working parameters. During a specific study concerning increasing the performance of the turbine blades it was observed that the overall performance of second and third generation blades has been improved significantly by adding the increased amount of Rhenium [10].

Increasing the life span of the blade can be done by coating the blade with an effective Thermal Barrier Coating (TBC). Thermal barrier coating is done on the turbine blades to reduce the temperature of the underlying substrate and also provide protection against oxidation and hot corrosion. One of the potential TBC is platinum aluminium or platinum chromium compound which constitutes the top coat of TBC [11]. Another study suggested that cast iron along with Zirconium coating is more beneficial due to low stress displacement and also easy to manufacture. A turbine blade after an extensive period of usage is being heat treated for 10 hrs keeping the heating rate at 600 °C per hour and cooling rate of about 200 °C per hour for restoring some damages in TBC, if possible. It was observed that the microstructure of ceramic coating will continuously change due to the grain growth and crack closes at high temperature after the heat treatment process [12]. The thickness of the TBC is another factor to be taken under consideration. An experimentation using the thermal barrier coating on the turbine blade shows that by adding 300 micrometre layer of thermal barrier coating on the blade leads to increase in life by 9 times [13]. The thermal insulation capability and stress level within the coating on the blade airfoil enhanced with the increase of topcoat thickness [14]. While operating the blade comes in contact with the air and the hot gases, the initial degradation occurs due to the oxidation of the aluminium from the platinum aluminium coating which form Aluminium Oxide on the surface which can be recognized by its significant red colour. Further this Al_2O_3 is removed eventually due to erosion that leads to increase in the oxygen percentage up to 26.64% and decrease in the percentage of aluminium by 10% [11]. Different TBCs have different compatibilities with the base alloys they are being coated on and the working parameters they are set to perform. 200 micron thick Zirconia coating used with 150 microns NiCrAlY layer was capable to reduce steady state temperature by 35.6%, steady state top surface heat flux by 15% and 3.72% more effective than equal thickness of Lanthanum Magnesium Hexaaluminate coating when used on the blade made up of Hastealloy-X [15] while with Inconel 718, NiCoCrAlY and $La_2Ce_2O_7$ on the top is the best suited for higher operating temperatures [16]. Procedure of coating the blades are operation specific so various processes are incorporated while coating a blade with TBC. Chemical vapour deposition, physical vapour deposition, thermal spraying, diffusion, multi laminated coating such as the advanced titanium nitride erosion coating system could be beneficial [17]. More modern procedures like plasma spraying, laser glazing, chemical vapour deposition and lased induced CVD processes are also being used for coating. All the process had their fair shares of pros and cons but laser induced CVD process was found to be give much better deposition rate and capable of producing thick and stable TBC [18].

Failure of the turbine blade is inevitable after an extensive period of service. Failure Analysis provides the information about the cause of the failure and how does it propagates along with any other flaws which eventually leads to the methods to rectifying those in future. Generally it is also noted that the leading edge is the hottest region of the blade [19] and the maximum stress occurs at the acute trailing corner results in creep damage [20]. Cracks was found on both the tip of leading and trailing edge of the blades and it is also discovered that the failure doesn't occurs due to the material defects but occurs due to oxidation of the thermal barrier coating on the top of the blade which leads to the propagation of cracks and hot corrosion which ultimately leads to failure. Regular maintenance of the turbine blade must be done for the reinforcement of thermal barrier coating, inspection of cracks, extension of Fatigue creep and micro structural disorientation. Failure analysis are performed after a particular period of service hours generally after 24000 hrs. Turbine blade made of Inconel 738 and used for 70 MW production line was in service for 24000 hours at the peak temperature 1086 degree Celsius. After performing grain structure evaluation, crack evaluation and stress analysis from which they found out that the maximum tension stress in the blade airfoil is 341 MPa. The grain structure analysis shows that at an airfoil particles are 33% to 80%, bigger than the root [21]. The failure didn't occur due to material defects but due to surface degradation due to oxidation of the Pt-Al coating and a service and repair session must be implemented after 24000-30000 hours of service which includes application of corrosion resistant alloy and friction dampers between the discs [22]. Second stage failure analysis are done when the blade gets failed completely shown either by complete degradation of the surface or breakage occurs. For a gas turbine blade used in power generation that stage generally comes after 73000 hours of service. An IN-738LC turbine blade failed due to multiple reason like pitting, fatigue, crack initiation due to hot corrosion and pitting is due to the bending stresses cracks are developed due to interdentride corrosion and propagated due to fatigue [23]. Damage can also cause due to external factors like domestic object damage due to the impact of the liberated components of the turbine engine on the blades which leads to premature and uncertain failure of the blade [24]. Thermal analysis is done before performing the mechanical analysis as to first determine whether the model is isothermal in nature or not. When it comes to structural and thermal analysis various factors like deformation, centrifugal forces, principal stresses and strain values and its positions are taken into consideration.

II. MATERIALS AND METHOD

A. *Materials Used*

Three materials are used for present analysis of the turbine blade. All the materials are used here are variants of Nickel based Inconel Superalloys namely, Inconel 718, 625 and 738. These three materials are mainly used to make turbine blades for usage in power plant.

INCONEL alloy 718 (UNS N07718/W.Nr. 2.4668) is a high-strength, corrosion-resistant nickel chromium material used at -423° to 1300°F. The age-hard enable alloy can be readily fabricated, even into complex parts. Its welding characteristics, especially its resistance to post weld cracking, are outstanding. The ease and economy with which INCONEL alloy 718 can be fabricated, combined with good tensile, fatigue, creep, and rupture strength, have resulted in its use in a wide range of applications. Examples of these are components for liquid fuelled rockets, rings, casings and various formed sheet metal parts for aircraft and land-based gas turbine engines, and cryogenic tankage. It is also used for fasteners and instrumentation parts.

INCONEL nickel-chromium alloy 625 (UNS N06625/W.Nr. 2.4856) is used for its high strength, excellent fabric ability (including joining), and outstanding corrosion resistance. Service temperatures range from cryogenic to 1800°F (982°C). Strength of INCONEL alloy 625 is derived from the stiffening effect of molybdenum and niobium on its nickel-chromium matrix; thus precipitation hardening treatments are not required. This combination of elements also is responsible for superior resistance to a wide range of corrosive environments of unusual severity as well as to high-temperature effects such as oxidation and carburization. The properties of INCONEL alloy 625 that make it an excellent choice for sea-water applications are freedom from local attack (pitting and crevice corrosion), high corrosion-fatigue strength, high tensile strength, and resistance to chloride-ion stress-corrosion cracking. It is used as wire rope for mooring cables, propeller blades for motor patrol gunboats, submarine auxiliary propulsion motors, submarine quick disconnect fittings, exhaust ducts for Navy utility boats, sheathing for undersea communication cables, submarine transducer controls, and steam-line bellows.

Alloy IN-738 is a vacuum melted, vacuum cast, precipitation hardened nickel-base alloy possessing excellent high temperature creep-rupture strength combined with hot corrosion resistance superior to that of many high-strength super alloys of lower chromium content. It is designed to provide the gas turbine industry with an alloy which will have good creep strength up to 1800 F combined with the ability to withstand long-time exposure to the hot corrosive environments associated with the engine. Alloy IN-738 exhibits tensile properties superior to and elevated temperature stress-rupture properties comparable to those of the widely used Alloy 713C along with substantially better sulphidation resistance. Two versions of Alloy IN-738 are produced: a high carbon version designated IN-738C and a low carbon version designated IN-738LC. The data reported in this bulletin were obtained primarily on high carbon (C) material. Where data are reported for the low carbon (LC) modification, they will be so indicated. Low carbon is needed in Alloy IN-738 for improved castability in large section sizes. Tensile and stress-rupture properties are not appreciably affected by the lower carbon content. Zirconium levels are lower in Alloy IN-738LC for improved castability.

B. Methodology

The following methodology is carried out during the present work;

- The literature review has been carried out to understand the steady structural analysis of turbine blade.
- The turbine blade required for the analysis purpose has been modelled using 3D-Modelling Software SOLIDWORKS V2016.
- After modelling of the blade, Finite Element Analysis has been carried out using ANSYS Workbench V14.0. Three different materials i.e.IN 718, IN 625 and IN 738 have been selected for the purpose of analysis.
- The analytical results of Deformation, Equivalent Stress, Equivalent Strain and Strain Energy are being generated using ANSYS for all the three materials.
- Validation of results from given parameter by comparing with previous published results has been carried out using the comparative analysis.

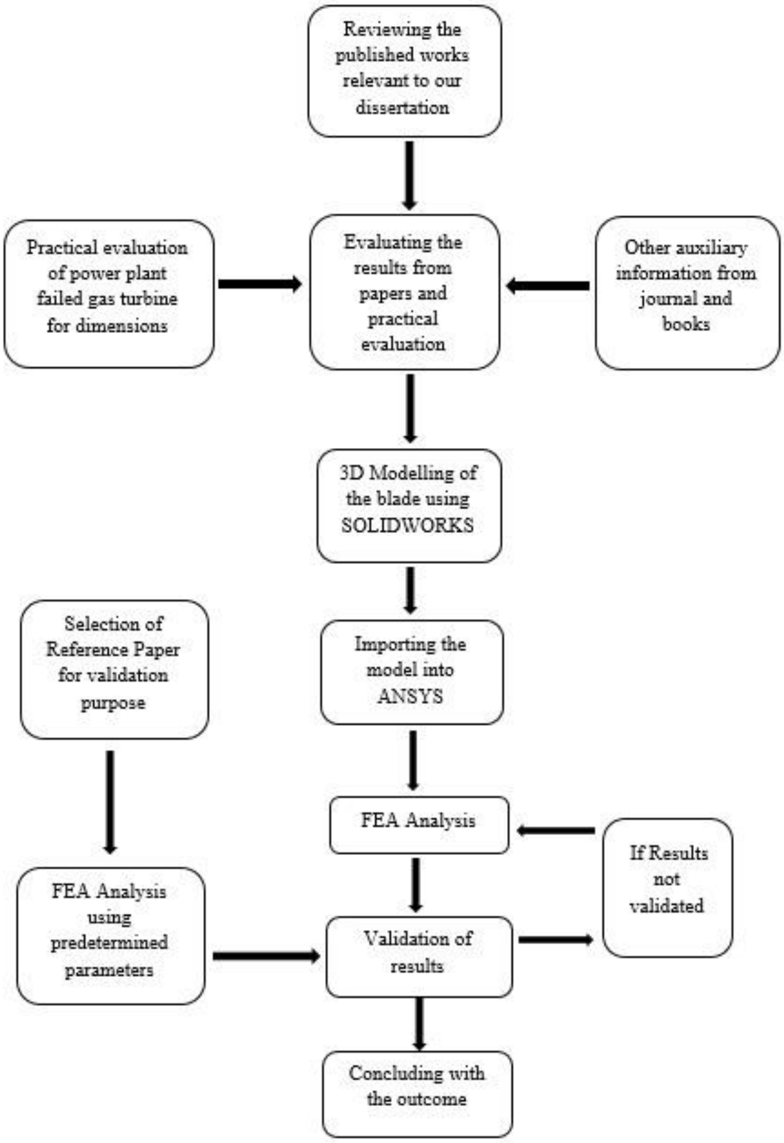

Figure 1. Procedures showing steps in Methodology

III. RESULTS AND DISCUSSION

This section shows the Deformation, Equivalent stress, Equivalent strain and Strain energy variation caused in the turbine blades in all three selected materials namely INCONEL 718, 625 and 738 w.r.t time. As the time interval increases input values of pressure varies from 2 MPa (20 Bar) to 4 MPa (40 Bar). 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 inlet gas temperature is maintained at of 1400^{0}C (Turbine inlet Temperature i.e. TIT).

Further design parameters are as follows;

- Effective Height of the blade is 350mm.
- Volume of the Bounding Box is 5.67 x 10^6 mm^3.
- Volume of the Blade (Volume of bounding box–Volume of the base) is 0.92 x 10^6 mm^3.
- Effective mass of the blade is 46.663 kg.

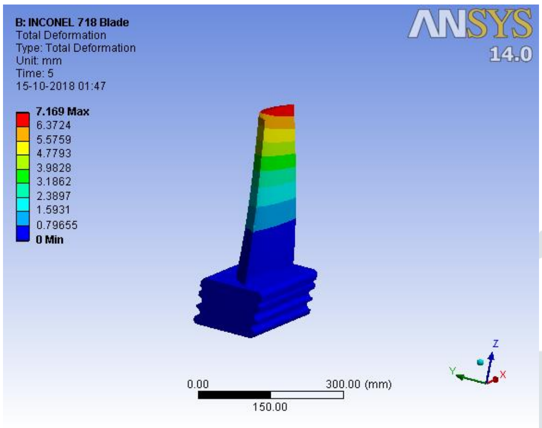

Figure 2. Deformation of Inconel 718 Blade

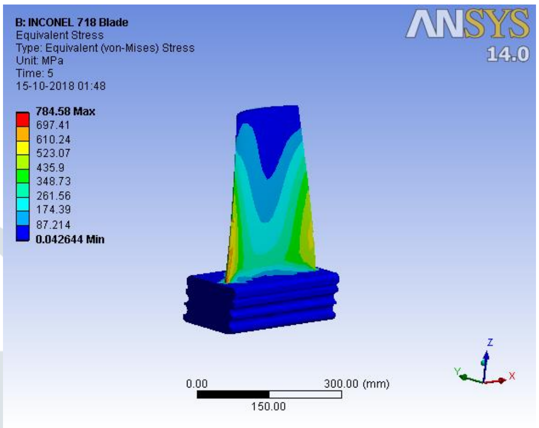

Figure 3. Eq. Stress distribution in IN 718 Blade

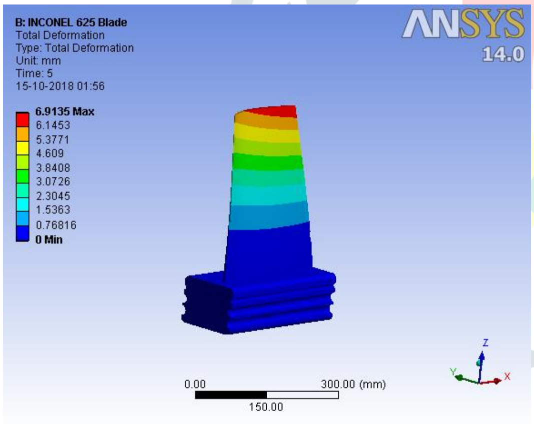

Figure 4. Deformation in Inconel 625 Blade

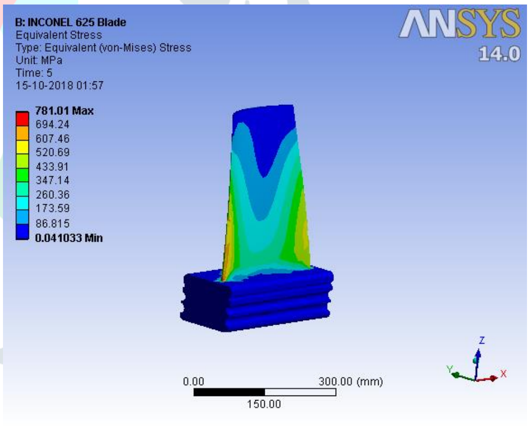

Figure 5. Eq. Stress distribution in IN 625 Blade

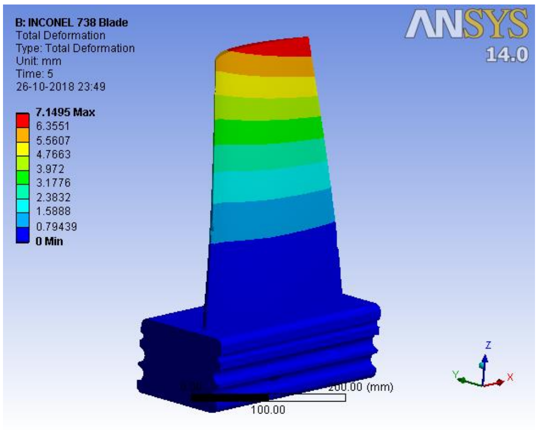

Figure 6. Deformation of Inconel 738 Blade

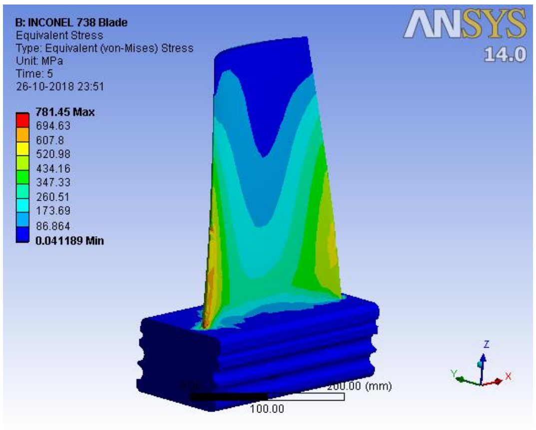

Figure 7. Eq. Stress distribution in IN 738 Blade

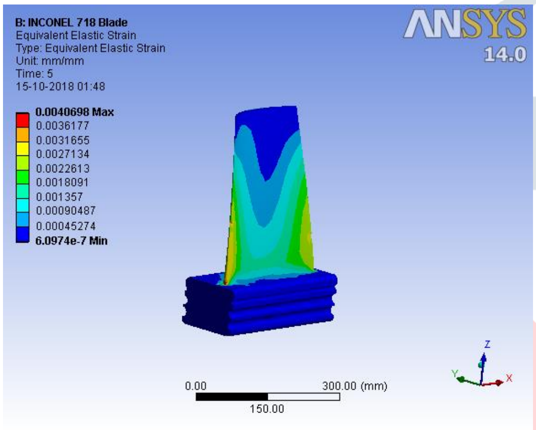

Figure 8. Eq. Strain distribution in IN 718 Blade

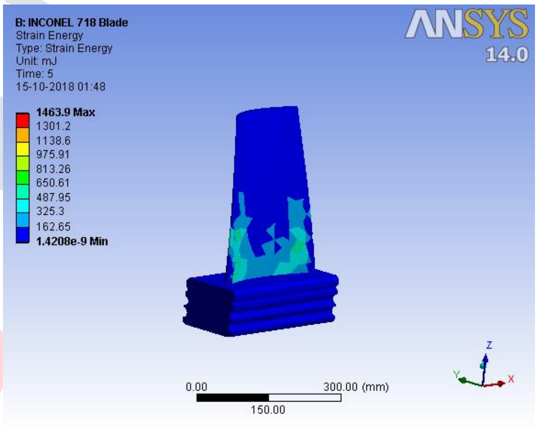

Figure 9. Strain Energy distribution in IN718 Blade

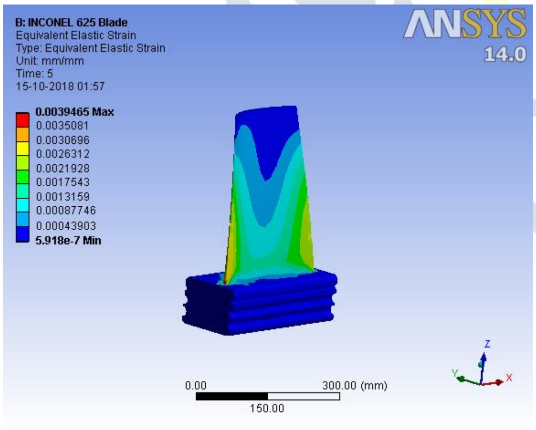

Figure 10. Eq. Strain distribution in IN 625 Blade

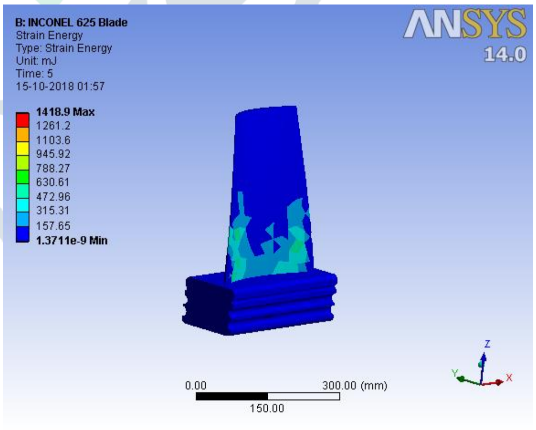

Figure 11. Strain Energy distribution in IN 625 Blade

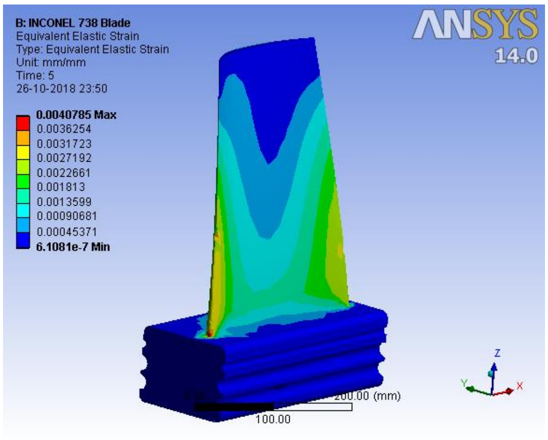

Figure 12. Eq. Strain distribution in IN 738 Blade

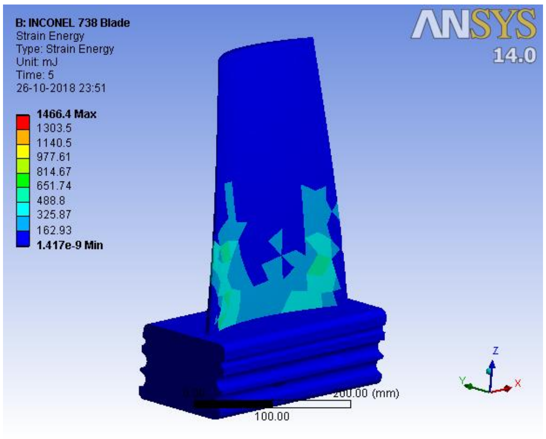

Figure 13. Strain Energy distribution in IN 738 Blade

It is evident from the Figures 2, 4 and 6 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 pressure of 4 MPa the maximum deformation observed in IN 718 is 7.169 mm, 6.9135 mm in IN 625 and 7.1495 mm in IN 738. IN 625 shows the least deformation among the three materials so considered to be better in the category of deformation.

Considering the Figures 3, 5 and 7 related to Equivalent stress, at the peak pressure of 4 MPa the Equivalent stress in IN 718 is 784.58 MPa, 781.01 MPa in IN 625 and 781.45 MPa in IN 738. 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 outcomes shows that the IN 625 shows the least stress accumulation among all three. But it is also evident that the other two doesn't lag in stress values significantly.

From figures 8, 10 and 12 it can be observed that at the peak pressure of 4 MPa the value of the Equivalent Strain is 4.0698×10^{-3}mm/mm in IN 718, 3.9465×10^{-3}mm/mm in IN 625 and 4.0785×10^{-3}mm/mm in IN 738. The outcomes shows that the IN 625 shows the least strain among all three. The Equivalent Strain shows almost similar demographics as the Equivalent 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.

From figures 9, 11 and 13 it can be observed that at the peak pressure of 4 MPa the Strain Energy is 1463.9 mJ in IN 718 blade, 1418.9 mJ in IN 625 blade and 1466.4 mJ in IN 738 blade. The results clearly shows that the concentration of the strain energy is least in blade made up of IN 625. The strain energy predominantly depends upon the value of Stress and Strain produced. As the stress concentration increases the strain energy also increases.

A. Validation of the Results

The value of the Strain Energy has been verified using the mathematical formulation for assuring the authenticity and precision of the software packaged generated data. The following results also checks the credibility of the values of Equivalent stress and Strain as the strain energy directly depends upon the product of stress and strain components. The comparison are as follows;

Table 1. Data of Validation for Strain Energy involving the values of Equivalent Stress and Equivalent Strain for IN 718.

Validation data for Strain Energy (mJ) for IN 718 Blade					
Time (sec) ➡	1	2	3	4	5
Results from FEA Software	365.97	571.82	823.42	1120.80	1463.90
Results from Mathematical Formulations	367.204	573.62	826.12	1124.22	1468.89
% Difference	0.3	0.31	0.32	0.35	0.32

As it is evident from the above tabular data that the margin of the difference is between 0-5 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. All the results are also verified using comparative analysis [8] following similar methodology and parameters. The margin in the input parameters has been similar as the margin of difference in the output parameters when compared for the verification.

IV. SUMMARY AND CONCLUSION

The present work focuses on the structural analysis of the turbine blade of a gas turbine used for power generation made of different Nickel based Super-alloys Inconel 625, Inconel 718 and Inconel 738. The four key parameters which provides the best indications about the suitability of the material taken here are Deformation, Equivalent Strain, Equivalent Stress and Strain Energy. 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:

- Inconel 625 is considered as the best suited material among the three selected alloys under the given working conditions.

- Although IN 625 is the considered as best suited one, the other two materials also yields results having very less difference.
- All the results generated here are under the safe and allowable limits.
- In actual practice, all the selected materials are used in power generation turbine blades.

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