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# Material Selection and Thermomechanical Performance Evaluation of Gas Turbine Blades using FEA

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***Abstract*— Blades in gas turbines should be capable of operating under severe thermomechanical loads, like high rotation speeds, high pressure and centrifugal loads, high axial loads, high tangential loads and may lead to undue stress, deformation and premature failures unless the appropriate materials are employed. The presented study presents a systematic thermo-mechanical study of five possible materials i.e., aluminium alloy, grey cast iron, magnesium alloy, stainless steel, and titanium alloy - using three-dimensional finite element method. The ANSYS was used to model and analyse a blade geometry using quadratic tetrahedra elements (SOLID187) based on patents. The final mesh consisted of 2974 nodes and 1405 elements and 1.13 was the difference in the stress which provided the convergence of the mesh. Mechanical loading (axial 16 N, tangential 995 N and centrifugal 39, 000 N at 8 000 rpm) was added and centrifugal loading was also adjusted to 80 to 120 percent. Constant thermal gradient was also used at 1030 o C (1680 o C surface of the blade and 650 o C root) too. In nominal loading, optimized von Mises stress of stainless steel and titanium alloy were 510.66 Mpa and 426.34 Mpa respectively. The safety factor of titanium and stainless steel was 39,000 N (1.947) and 39,000 N (1.175), which was structurally unsafe of aluminium (0.965), magnesium (0.616) and cast iron (0.504). Its safety factor at full load of 120 percent was 1.708. According to the thermo stress analysis, the lowest experimental thermally induced stress of titanium alloy (1543 Mpa) was lower than stainless steel (4566 Mpa). The main input of the work is the structural and thermal performance of the most common engineering materials used when subjected to varying centrifugal forces to 120 percent of working conditions with mesh convergence and analytical confirmation (2.98 percent error). These findings make titanium alloy the material that is most structurally stable as it possesses the highest strength to mass ratio, containment of deformation and thermal indifference. The suggested methodology provides a rationalized computational model of selecting the turbine blade material, preliminary design check, and, later optimization of the high-speed rotating parts production using the CAD/CAM.**

***Keywords*— Turbine blade, Material, Ansys, FEA Analysis, Thermal Analysis, Static Analysis, Stress, Deflection**

**Novelty: The study is innovative in the sense that it offers a systematic compliant examination of five candidate materials of gas turbine blades at a combination of structural and thermal loading situations. The realistic operating conditions including the centrifugal forces variation to 120 percent of the nominal load are considered to explore the most reliable material structural use in turbine blades.**

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## I. INTRODUCTION

Gas turbine blades put under the extreme thermomechanical conditions, which involve high temperature, high rotation and continuous mechanical loading. These severe working conditions give rise to severe centrifugal forces, bending stress as well as thermal gradients, and they may result in over centrifugal deformation, crack propagation, creep damage and structural breakdown in advance of time. "It is therefore necessary to ensure that appropriate materials are chosen to ensure structural stability, great level of security in operations and a long life. A series of engineering materials have been recommended in the application of turbine blades with each of them having individual mechanical and thermal characteristics. Aluminium and magnesium have alloys which are lightweight, but they are not as massive as aluminium and magnesium but they are also less thermal resistant. Cast iron is brittle as well as rigid. The stainless steel has good mechanical strength but increased density. Titanium alloys provide a perfect combination of high strength, medium density and increased thermal resistance. Although studies on coating technologies, cooling techniques and high-quality alloys were already conducted, the comparison of the most popular structural materials in the combined structural and thermal loading system and centrifugal forces of various magnitudes was not carried out extensively. The aim of the current paper is to provide this gap by performing a systematic finite element analysis of five candidate materials in a realistic operating environment of a turbine.

### A. Blade selection criteria

Gas turbine blades operate under extreme thermomechanical environments and must withstand high operating temperatures, significant centrifugal forces generated by rotational speeds between 3,000 and 8,000 rpm, and bending stresses induced by aerodynamic gas pressure. In addition, prolonged exposure to combustion gases such as $CO_2$, CO, and $O_2$ may result in oxidation, corrosion, and material degradation. Therefore, turbine blade materials must exhibit high yield strength, thermal stability, creep resistance, oxidation resistance, and adequate fracture toughness to ensure long-term structural reliability. Nomenclature: F_a= Axial Force, F_t= Tangential Force, F_c= Centrifugal Force.

## II. LITERATURE REVIEW

Prasad Gudimetla et al. (2014). Optimum Material Analysis of a Gas Turbine Blade on Reverse Engineering (RE) and FEA. In this study, they were involved in formulating the best material that would be used in the gas turbine blades in which the preliminary design specifications were not available. They gave the reverse engineering of the 3D model of the blade and analyzed it in ANSYS software with different loading conditions. The five materials are considered so that Aluminium alloy, grey cast iron, Magnesium alloy, Stainless steel and Titanium alloy are contrasted with each other and it has been found that Titanium alloy material is the most suitable material to be used as a gas turbine blade [1]. Alessandro Innocenti et al. (2016). The impact of Upgraded Cooling System and New Materials of Blades on the real gas turbine performance. The researchers of this paper have analyzed the influence of the improved cooling systems and quality of material used in making the blades on the performance of gas turbines. The results confirmed that the optimization of cooling techniques reduces the quantity of coolant required and enhances with respect to efficiency even though hotspot may occur locally in some of the components of blades. High temperature resistant materials that have contributed to the increment in the operational reliability were envisaged in the paper [2]. Pradip Gedam et al. (2017). Thermal Study of gas turbine blade barrier coating material (TBC) of Gas turbine blade. The researchers in this research have investigated how the special coating can protect the gas turbine blades and it is exposed to high temperature and pressure by the hot combustion gases. The turbine blades are made by utilizing a substance known as Inconel-713 and also coating is experimented with Yttria Stabilized Zirconia, Aluminium oxide and Lanthanum Hex aluminate, all tests are carried out on coating of 0.5 mm. In this study, the blades could be measured by computer simulation based on the level of heating, bending, and stress when subjected to such extreme conditions. The obtained results set the YSZ coating as the most suitable one as it reduces the stress and deformation more than any other material do [3]. K. Sandhya et al. (2025). The article is named Material Selection and Fatigue Analysis of Gas turbine blades to enhance the performance. This study revealed that, the material, which is most appropriate to the gas turbine blades, differentiates the material, which constitutes of high temperature and recurrent strains. Moreover, the authors mentioned CAD modelling and Ansys to test these five materials including IM 834, Nimonic 80A, Inconel 617, CMSX-4 and even Inconel 718. It was determined at the end of the process based on this that IM 834 is the most appropriate one [4]. Venkata Raman et al. (2016). Critical Review on Cooling Performance and Failure Analysis of gas turbine. Scholars have studied different cooling techniques used in gas turbines and the need to use them so that the blades can be safe under the conditions of the extreme heat. Internal cooling, external cooling, Film cooling, and advanced cooling technique are also defined by authors and provided an account of the blade failures, such as cracks, creeps, and oxidation [5]. I. Ullah et al. (2023). Research on Gas Turbine Blade Materials to possess an effective system of energy. The authors in this study had to experiment with different materials to be employed as the gas turbine blades to determine and recommend the best material in high temperature and pressure setting. Titanium alloy, magnesium alloy and aluminium alloy were analysed by ANSYS simulations. The results revealed that titanium alloy was more stable at high temperatures, low-stress levels, and less deformation and, therefore, it was the most suitable material of the blade [6]. V. V. Savinkin et al. (2020). Enrichment of the Turbine Blade Surface Phase Structure Recovered by Plasma Spraying. The authors investigated the technique of the restoration of the surface of turbine blades using the plasma spraying technology. The method increased fatigue and adhesion as well as the surface hardness and reduced defects. In this paper, structural and life of turbine blades were found to increase when optimized by plasma spraying [7]. N. Chouchane et al. (2024). Enhancement of the Gas Turbine Performances: Numerical thermal analysis of gas turbine blades using Ceramic Coating (MgO). The CFD and the analytical method were used in this paper to investigate the method of influencing MgO ceramic coating on the thermal performance of turbine blades. The coating reduced the heat penetration and increased the stability of temperature that confirmed that MgO was a suitable thermal resistant coating on turbine blades [8]. B. Pitchia Krishnan et al. (2021). Redesign and estimation of performance of horizontal axis wind turbine blade. The authors have applied a wind turbine blade to reshape the turbine blade, using a combination of aerodynamic analysis, FEA and optimization techniques. The redesigned blade was found to have a weight reduction of about 39 percent and retained structural strength of the blade and improved the aerodynamic efficiency [9]. A. B. Animasaun et al. (2025). Design and optimization of Wind Turbine Performance through advanced materials. This review has discussed new composite materials and smart materials and aerodynamic optimization techniques that have been applied to improve efficiency and longevity of wind turbines. The benefits such as higher strength-to-weight ratio and reduced maintenance were revealed in the paper with the cost and recyclability factors [10]. A. E. H. Ferrak et al. (2024). Thermomechanical Investigation into a Ceramics coated composite material Gearbox Turbine Blade. The test was the thermomechanical test of turbine blades manufactured with various alloys and composite materials to which a ceramic coating was applied. They discovered that composite blades that were covered with ceramics exhibited a lower deformation, increased thermal resistance, and increased life, compared to conventional material [11]. P. Puspitasari et al. (2021). The article is called Failure Analysis of a Gas Turbine Blade: A Review. This review has discussed important causes of failure of turbine blades which are fatigue, creep, corrosion, oxidation and erosion. The authors have also noted the importance of improved coating, high-quality materials as well as maintenance strategies such that the dependability and life of turbine blades can be prolonged [12]. B. Swain et al. (2020). The Development of Materials of Gas turbine blades Failure Analysis and Development. The authors updated the mechanics of turbine blades failure and the tendencies of material development. The authors have pointed out the erosion wear, corrosion, fatigue and oxidation as the key factors causing failure and the application of high-level coating as well as superalloys which improves the performance of blades [13]. H. P. Singh et al. (2020). The blade of a gas turbine of different materials is analyzed through computational analysis. This paper entailed a comparison of titanium alloy, Nimonic 80A, INCONEL 617, and rhenium through conducting FEA structural, thermal and modal. Nimonic 80A had the least deformation, better vibration stability, and, suitable cost, hence, it was the most suitable material to be used in turbine blades [14]. B. Deepanraj et al. (2011). Finite Elements Analysis of Theoretical Gas Turbine Blade. Through FEM, the authors were able to compare the cooling of turbine blades with different cooling holes. The results showed that eight cooling holes provided the best temperature distribution (approximately 800 C) and reasonable degrees of stress in the improvement of turbine blades performance [15]. However, the problems of the high degree of stress, exhaustion, and depression of blades still exist. We performed the review of these studies and were able to determine the gaps in the research and formulated the problem statement which will be outlined in the next section.

*A. Research gaps*

- Some studies only focus on surface coating enhancements and they only give little attention towards comparing core material with them.
- Lot of researchers are avoiding the testing of turbine blades for combined both thermal and structural loading at the same time.
- The influence of varying rotational speeds and the resulting centrifugal forces has not been explored thoroughly.

- A direct comparison among widely used materials such as aluminium, cast iron, stainless steel, and titanium is still missing. The present study addresses these shortcomings by applying Finite Element Analysis (FEA) to evaluate and compare five materials under realistic turbine conditions to identify the most suitable one. For that the given problem statement are decided which are mentioned in next section.

*B. Problem statement*

Gas turbine blades are subjected to combined centrifugal, axial, tangential, and thermal loads during operation. Inadequate material performance under these conditions leads to excessive stress concentration, deformation, and reduction in fatigue life.

Therefore, a systematic thermomechanical evaluation of candidate materials is required to identify the most structurally reliable option for turbine blade applications. From these problem statement and literature, the objectives are decided which are mentioned in next section.

*C. Objectives*

- To develop a three-dimensional CAD model of a gas turbine blade based on patent-derived geometry.
- To perform static structural and steady-state thermal analyses using finite element methods.
- To evaluate stress distribution, deformation, and factor of safety for selected materials under varying centrifugal loads.
- To compare thermomechanical performance and identify the most suitable material for turbine blade applications.
- To establish a methodology applicable to future design validation and manufacturing optimization. Based on these objectives the following methodology is adopted.

## III. METHODOLOGY

This was carried out by designing a model of a 3-dimensional turbine blade in SolidWorks which was imported to ANSYS to carry out a finite analysis. The root of the blade was modelled as a support which was attached to simulate rotor attachment. Combination was made of mechanical loads i.e., axial force (16 N), tangential force (995 N), and centrifugal force (39, 000 N at 8,000 rpm). To simulate the changes in the speed, centrifugal force was adjusted between 80 and 120 percent of the nominal operating load. To obtain numerical accuracy and convergence of the solution, a fine tetrahedron mesh was developed. Static analysis of the structure was performed to determine von Mises stress and deformation. A steady-state thermal test was conducted under conditions of blade surface temperature at 1680℃ and root temperature at 650℃ yielding a thermal gradient of 1030 ℃ to calculate the thermal stresses. Five materials were taken in case of aluminium alloy, grey cast iron, magnesium alloy, stainless steel and titanium alloy. The allocation of material properties was done using the standardized mechanical data.

*A. Theoretical Analysis formulation*

Theoretical analysis was done to ascertain the results of loading and deformation as received in ANSYS. The major forces acting on the turbine blade are the centrifugal, thermal and bending stresses that occur in the turbine blade during high-speed rotation. The only formulae are listed below.

*Centrifugal force*

The centrifugal force acting on the blade is given by,

$$F_c = m\,\omega^2\,r \tag{1}$$

Were,
$F_c$ = Centrifugal force in (N)
m = mass of blade (kg)
ω = Angular speed (rad/sec)
r = Distance from axis of rotation to centroid of blade (m)
For rotational speed 8,000 rpm

$$\omega = 2\,\pi\, \times \frac{rpm}{60} \tag{2}$$

$$m \times r = \frac{F_c}{\omega^2} \tag{3}$$

From the simulation, the total centrifugal force was 39,000 N. This means the combined effect of the blade's mass and its distance from the centre matches realistic conditions for a rotating blade. And their results are mentioned in table no. 4.

*Bending stress at blade root*

For a blade approximated as a cantilever beam with a resultant centrifugal load Fc acting at the centroid, the bending moment at the root is,

$$M = F_c \times a \tag{4}$$

where,

a = Distance to the root to centroid

I = Moment of inertia

C = Distance from neutral axis

The bending stress is given by,

$$\sigma_b = \frac{Mc}{I} \tag{5}$$

This formula helps validate the FEA results for the von Mises stress at the blade root.

*Factor of Safety*

The factor of safety is obtained using von mises yield criterion,

$$FOS = \frac{\sigma_y}{\sigma_v} \tag{6}$$

Where,

$\sigma_y$ = yield strength of material

$\sigma_v$ = Von-Mises equivalent stress

The obtained factor of safety for different materials is mentioned in table no. 2

*Thermal stress estimation*

Thermal stress develops due to temperature variation along the blade surface and root. It can be estimated as,

$$\sigma_{th} = \frac{E\alpha\Delta T}{1-v} \tag{7}$$

Where,

E = Young's Modulus

$\alpha$ = Coefficient of thermal expansion

$\Delta T$ = Temperature difference

$v$ = Poisson's ratio

The obtained thermal stresses are mentioned in Table 6.

*Material Properties for turbine blade*

TABLE I: MATERIAL PROPERTIES

| Material | Density ($\frac{Kg}{m^3}$) | Yield Strength (MPa) | Young's Modulus (GPa) | Poisson's Ratio |
|---|---|---|---|---|
| Aluminium Alloy | 2800 | 410 | 72 | 0.33 |
| Cast Iron | 7200 | 250 | 170 | 0.25 |
| Magnesium Alloy | 1800 | 250 | 45 | 0.35 |
| Stainless steel | 7920 | 600 | 194 | 0.3 |
| Titanium Alloy | 4460 | 830 | 110 | 0.34 |

*B. Computational Analysis*

*Static structural analysis of turbine blade*

Static analysis is used to study how a structure behaves under constant loads, without considering effects like vibrations or damping that come from changing loads. It helps determine the stresses, deflections, and reaction forces when the structure is exposed to steady forces.

In this work, the finite element model of the gas turbine blade is analysed using static structural analysis & steady-state analysis in ANSYS during the solution stage.

*3D CAD Modeling*

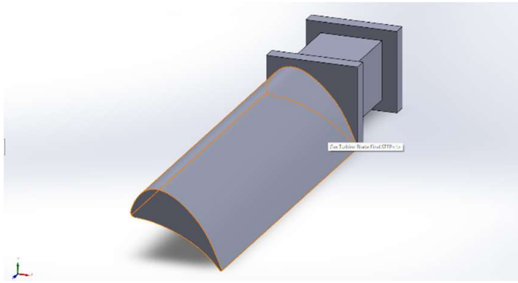


Fig. 1. (a) CAD Model

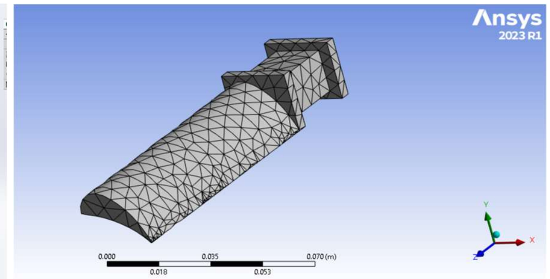



Fig. 2. (b) Meshing

*Boundary conditions*

The gas turbine blade is attached to the rotor. Since half of the blade root is embedded inside the rotor, that part is considered completely fixed. This means the root cannot move in any direction (no displacement in X, Y, or Z) and it also cannot rotate (no rotation about X, Y, or Z). This setup is shown in Fig. 3.

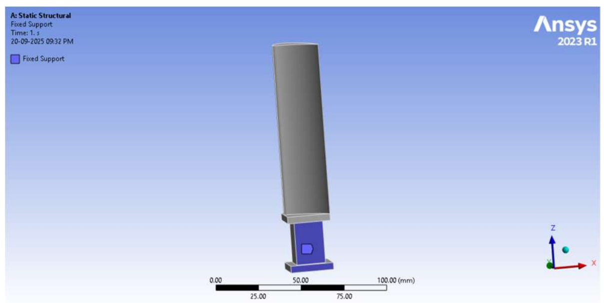



Fig. 3. Fixed Support (Blade)

*Blade Loading*

Fig. 4. shows the gas turbine blade is subjected to three major loads: axial, tangential, and centrifugal. The axial load acts along the X-axis, the tangential load is directed along the Y-axis, and the centrifugal load acts outward in the radial direction, parallel to the Z-axis. For the present rotor configuration, the axial force is 16 N, the tangential force is 995 N, and the centrifugal force is 39,000 N. In the ANSYS model, the applied forces were imposed at the blade centroid to simulate resultant loading conditions.

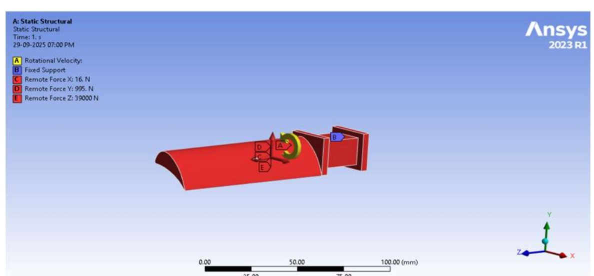



Fig. 4. Forces in x, y, z direction

*Static analysis of blade centrifugal force*

Fig. 5. (a)-(e) show how different materials (Titanium, Magnesium, Aluminium, etc.) respond when centrifugal forces act on the blades. The highest stress always occurs near the centre of the blade. For Titanium, the stress reaches about 426.34 MPa, For Aluminium Alloy, the stress reaches about 424.8 MPa, For Magnesium Alloy, the stress reaches about 422.12 MPa, For Cast Iron, the stress reaches about 496.06 MPa, For Stainless steel, the stress reaches about 510.66 MPa, at normal condition. When compared with the strength of each material, the results show that Stainless steel and Titanium alloy have factors of safety of 1.175 and 1.947, meaning they can handle the applied forces without failing. Overall, the stresses produced in Stainless steel and Titanium blades

are all within safe limits, so the blades would not fail under these conditions. The table 5. shows how safe different blade materials are when the turbine speed changes. As the speed increases, the centrifugal force on the blade also increases (from 80% up to 120% of the normal load of 39,000 N). This causes higher von Mises stress in the material, which is then compared with its yield strength to calculate the factor of safety (FOS) which are mentioned in table no. 3.

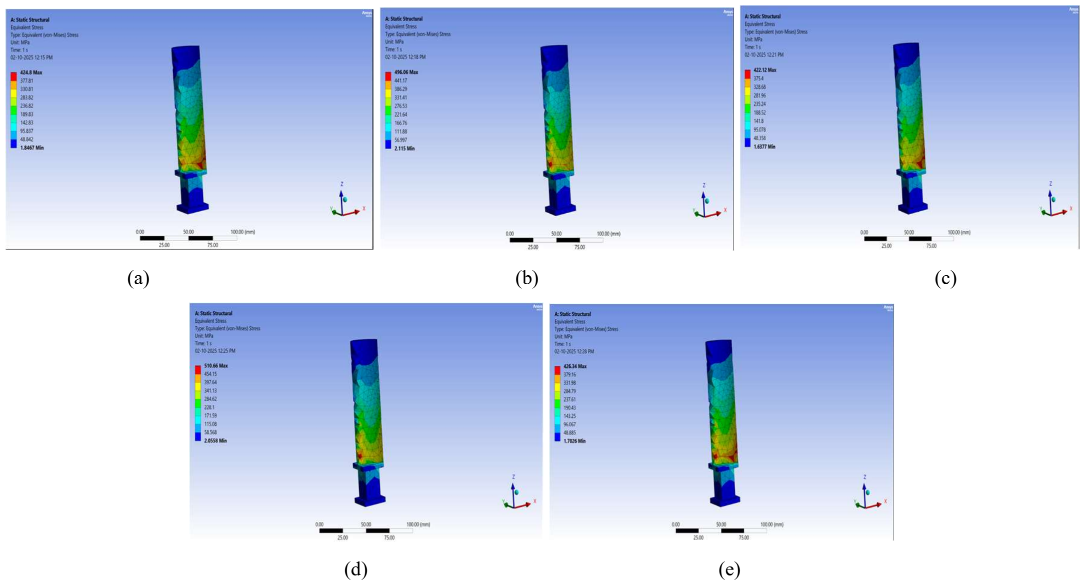



Fig. 5. Von Mises stress distribution in turbine blade due to centrifugal loading for (a) aluminium, (b) cast iron, (c) magnesium, (d) stainless steel, and (e) titanium.

Table 4 and fig. 6. indicate the deflections of the blade tip of various materials at normal centrifugal force. In all directions, magnesium alloy registered the highest deflections, in the Y-axis, it was 3.65 mm, which is weak and unstable. The bending of aluminium alloy was also large, especially in the Y- direction, and this makes it unreliable. Cast iron that was grey cast iron had mediocre deflections, but since it was brittle, it is not a safe material to use in turbines. Stainless steel was lowest in deflections; hence it is highly stiff and it does not bend easily. Titanium alloy experienced a little bit more deflections than stainless steel though they were within safe ranges and there is a combination of the alloy with its enhanced strength, which gives the greatest overall performance. It is analyzed that Ti blade is the most appropriate candidate.

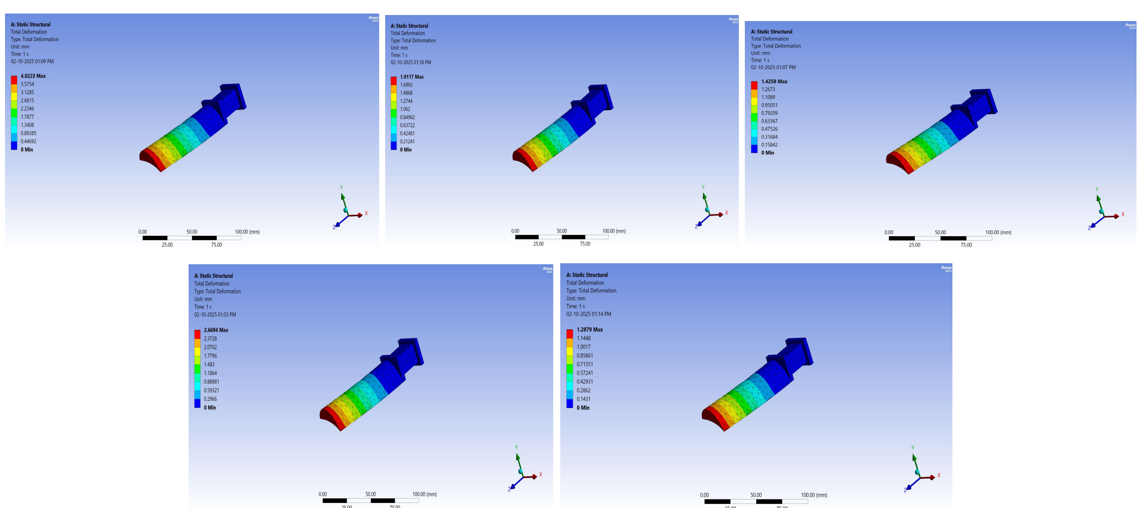
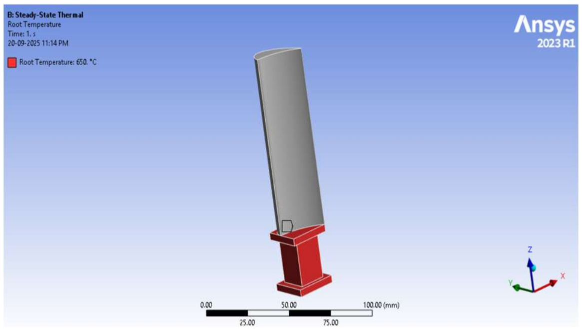


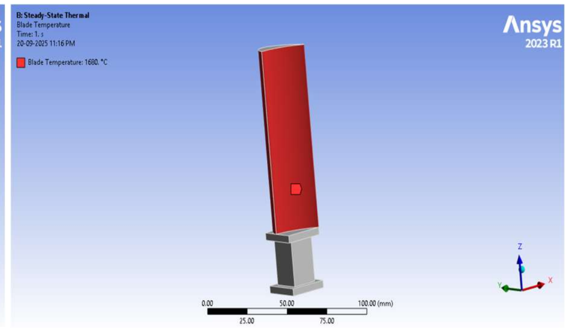
Fig. 6. Typical tip deflections in the x-, y- and z- axes

*Steady-state thermal analysis*

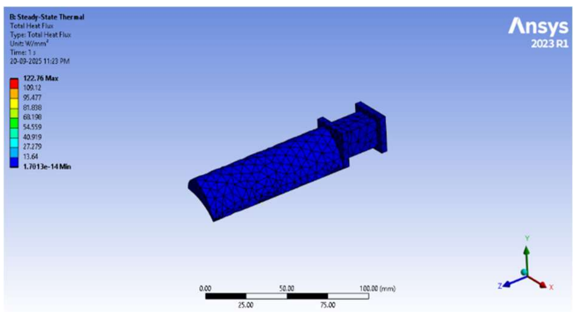
In the case where the temperature is kept constant over time, the steady-state thermal analysis is used to monitor how a part distributes heat and its transport. This is important in the case of turbine blades because of the high temperatures in which they work and the fact that knowledge of the heat distribution helps in system checking their performance, life and the behaviour of their materials. The temperature of the root in the present experiment was 650 o C and a blade surface temperature of 1680 o C that generated a thermal gradient of 1030 o C. We will then obtain temperature distribution, Total heat flux, Directional heat flux over blade under normal loading condition, represented figures are the results of this analysis.



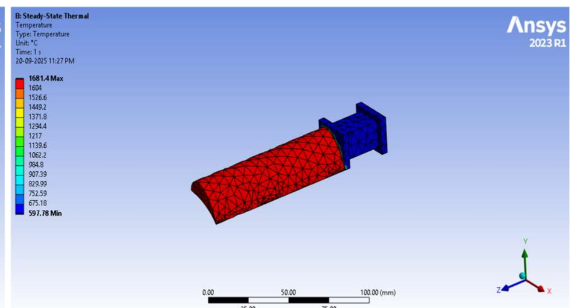

(a) Root temperature



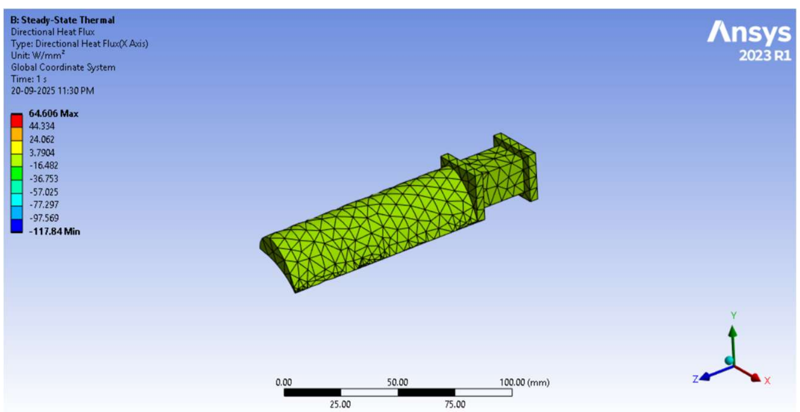

(b) Blade temperature




(c) Total heat flux




(d) Temperature distribution




(e) Directional heat flux

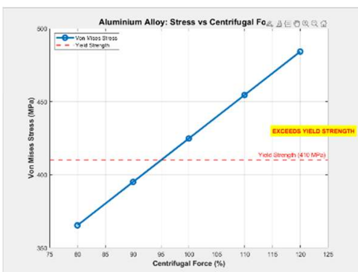
Fig. 7. Steady-state thermal analysis

## IV. Results

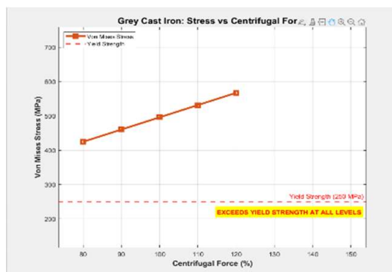
The gas turbine blade model was created using the SolidWorks and finite element method and analysed in ANSYS under the specified loads and boundary conditions. The results of this analysis are explained below.

*A. Blade Stresses in different materials due to varying centrifugal force*

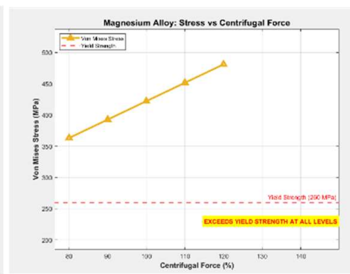
Fig. 8. (a) Aluminium Alloy As the turbine speed increases, the stress in aluminium also goes up. At normal operating speed (100% load), the stress goes above its strength limit (410 MPa). This indicates that aluminium alloy exceeds its yield strength under nominal operating conditions and therefore does not satisfy structural safety requirements. (b) Grey Cast Iron The stress in cast iron is already much higher than its strength (250 MPa), even at 80% speed. This indicates that grey cast iron is structurally inadequate for turbine blade applications under the investigated loading conditions. (c) Magnesium alloy exhibits stress values exceeding its yield strength (260 MPa) across the investigated loading range, indicating inadequate load-bearing capacity for turbine blade applications. (d) Stainless Steel, the stress in stainless steel increases with speed but mostly stays just under its strength limit (600 MPa). At full speed, there is a little safety left (about 89 MPa), and even at 120% speed it is only just safe. Stainless steel remains within its yield limit; however, the available safety margin decreases significantly at elevated loading conditions. (e) Titanium alloy demonstrates superior structural performance compared to the other evaluated materials. Its stress levels always stay well below its strength of 830 MPa. At normal operating speed, it has a large safety margin of about 364 MPa, and even when the load increases by 20%, it remains safe. Titanium alloy demonstrates superior structural performance and emerges as the most reliable material among the evaluated candidates.



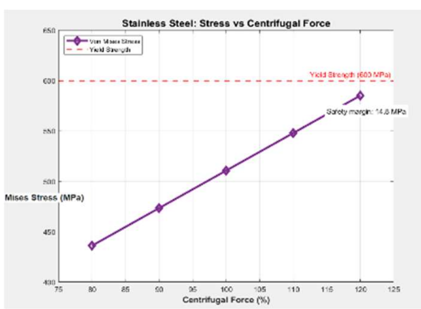

(a)



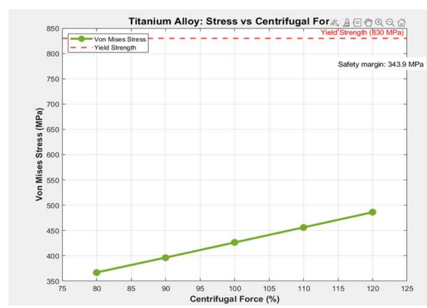

(b)




(c)




(d)




(e)

Fig. 8. Stress vs centrifugal force

*B. FOS Estimation*

By doing the theoretical calculation this factor of safety is obtained for all the material by varying its load. And finally, it is found that the titanium alloy having a FOS is 1.94 at normal load of 39,000 N. Similar for all other materials is calculated.

TABLE III: FACTOR OF SAFETY (FOS) FOR TURBINE BLADE MATERIALS

| Material | Yield Strength (MPa) | FOS 80% | FOS 90% | FOS 100% | FOS 110% | FOS 120% |
|---|---|---|---|---|---|---|
| Aluminium Alloy | 410 | 1.122 | 1.038 | 0.965 | 0.902 | 0.847 |
| Grey Cast Iron | 250 | 0.589 | 0.543 | 0.504 | 0.470 | 0.441 |
| Magnesium Alloy | 260 | 0.716 | 0.662 | 0.616 | 0.576 | 0.541 |
| Stainless Steel | 600 | 1.376 | 1.267 | 1.175 | 1.095 | 1.025 |
| Titanium Alloy | 830 | 2.261 | 2.093 | 1.947 | 1.819 | 1.708 |

So, from Table 3, stainless steel looks like the only usable option, but it is still close to the limit. For real turbine blades, a stronger material such as titanium is preferred because it provides a higher safety margin.

TABLE IV: BLADE TIP DIRECTIONAL DEFORMATION DUE NORMAL CENTRIFUGAL FORCE IN DIFFERENT MATERIALS

| Material | Deflection (mm) | | |
|---|---|---|---|
| | X | Y | Z |
| Aluminium Alloy | 1.11 | 2.40 | 0.33 |
| Grey Cast Iron | 0.69 | 1.23 | 0.16 |
| Magnesium Alloy | 1.59 | 3.65 | 0.54 |
| Stainless steel | 0.64 | 1.11 | 0.15 |
| Titanium Alloy | 0.85 | 1.69 | 0.22 |

TABLE V: CENTRIFUGAL FORCES WITH SPEED AND VELOCITY

| Target Force (%) | Centrifugal Force (N) | Speed (rpm) | Rotational velocity (rad/s) |
|---|---|---|---|
| 80 | 31,200 | 7,155 | 749.3 |
| 90 | 35,100 | 7,590 | 794.8 |
| 100 | 39,000 | 8,000 | 837.8 |
| 110 | 42,900 | 8,390 | 878.7 |
| 120 | 46,800 | 8,763 | 917.7 |

TABLE VI: THERMAL STRESS

| Material | E (MPa) | α (1/°C) | ΔT (°C) | ν | σt (MPa) |
|---|---|---|---|---|---|
| Aluminium Alloy | 72,000 | $23 \times 10^{-6}$ | 1030 | 0.33 | 2,550 |
| Cast Iron | 170,000 | $11 \times 10^{-6}$ | 1030 | 0.25 | 2,571 |
| Magnesium Alloy | 45,000 | $24 \times 10^{-6}$ | 1030 | 0.35 | 1,710 |
| Stainless Steel | 194,000 | $16 \times 10^{-6}$ | 1030 | 0.30 | 4,566 |
| Titanium Alloy | 110,000 | $9 \times 10^{-6}$ | 1030 | 0.34 | 1,543 |

## V. SUMMARY OF STATIC ANALYSIS

In a gas turbine, the blades experience very high centrifugal force, which is the main reason they fail. From the analysis of the five materials:

- Aluminium Alloy is only safe at lower speeds, but at normal load it already goes beyond its strength, so it cannot be trusted.
- Magnesium alloy and grey cast iron exhibit insufficient structural capacity, with stress levels exceeding yield strength even under reduced loading conditions, thereby limiting their applicability.
- Stainless Steel manages to stay safe even up to 120% load, but the safety margin is very small at higher speeds.
- Titanium Alloy performs the best, with plenty of safety margin even at 120% load, making it the most reliable choice. Based on the comparative structural evaluation, titanium alloy emerges as the most reliable material for turbine blade applications under the investigated loading conditions. The results are summarized Table 3.

## VI. VALIDATION

### *A. Analytical and Numerical Stress Comparison*

The bending stress at the blade root was analytically estimated using classical beam theory as described in Section 4.1. The bending stress was calculated using:

$$\sigma_b = \frac{Mc}{I} \tag{8}$$

For the nominal centrifugal load of 39,000 N, the analytically calculated bending stress was 414 MPa. The corresponding maximum von Mises stress obtained from finite element analysis for titanium alloy was 426.34 MPa.

TABLE VII

| Method | Maximum Stress (MPa) |
|---|---|
| Analytical Calculation | 414 |
| Finite Element Analysis | 426.34 |

The close agreement between analytical and numerical results confirms the correctness of boundary conditions, loading implementation, and geometric modeling.

*B. Percentage Error Estimation*

The percentage deviation between analytical and FEA results was calculated using:

$$\text{Error (\%)} = \frac{\sigma_{\text{FEA}} - \sigma_{\text{Theory}}}{\sigma_{\text{Theory}}} \times 100 = \frac{426.34 - 414}{414} \times 100 = 2.98\ \% \qquad (9)$$

The obtained deviation of 2.98% is within acceptable limits for structural finite element analysis, indicating strong agreement between simplified analytical theory and three-dimensional numerical modeling. The minor variation arises due to geometric complexity and stress concentration effects captured by FEA but not considered in beam theory.

*C. Comparison with Previous Studies*

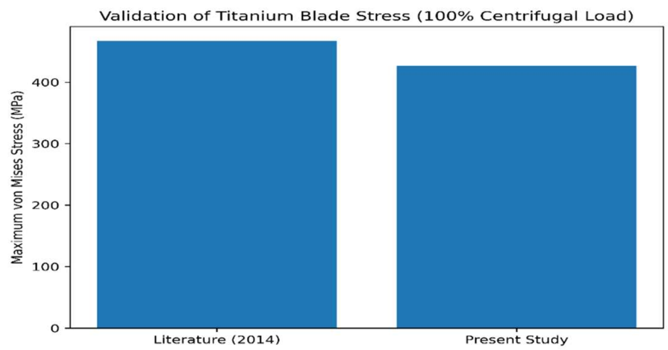



Figure 10. Comparison of present study with Literature

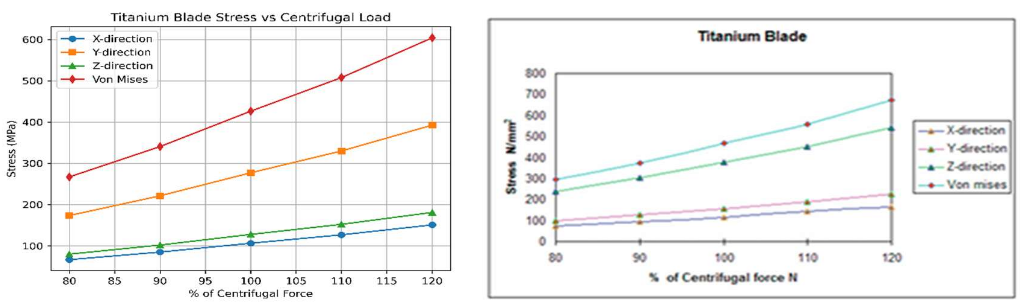



Figure 11. Stress vs Centrifugal Force

The stress variation trends obtained in the present study show strong agreement with the results reported in the literature. The directional stress components (X, Y, and Z) exhibit identical proportional behavior, with Y-direction stress dominating under centrifugal loading. The maximum von Mises stress at 100% load shows a deviation of 8.71%, which lies within acceptable limits for finite element validation. Furthermore, the linear increase in stress with increasing centrifugal load confirms correct stiffness representation and boundary condition implementation. The agreement in trend, magnitude, and stress distribution validates the accuracy and reliability of the developed finite element model.

## VII. Discussion

The comparative thermomechanical analysis confirms that titanium alloy exhibits the most balanced structural performance under combined mechanical and thermal loading conditions. At a nominal centrifugal load of 39,000 N, it maintains a factor of safety of 1.947, which remains above 1.7 even at 120% loading. This is mainly due to its high yield strength (830 MPa) and moderate density (4460 kg/m³), providing an excellent strength-to-weight ratio for high-speed rotating components. Centrifugal stress increases with material density; therefore, stainless steel experiences higher stresses due to its higher density, leading to reduced safety margins at elevated speeds. In contrast, titanium alloy shows lower centrifugal stress with sufficient stiffness, ensuring better deformation control and structural stability. From a thermal perspective, titanium alloy demonstrates the lowest thermal stress (1543 MPa) due to its low coefficient of thermal expansion, while stainless steel exhibits significantly higher thermal stress. Reduced thermal stress improves resistance to fatigue and material degradation during continuous operation. Additionally, the two-phase microstructure of titanium alloys enhances strength, ductility, and resistance to crack propagation under cyclic loading. Although titanium alloys have lower temperature limits compared to nickel-based superalloys, they offer advantages in weight reduction and cost, making them suitable for medium-temperature turbine applications. Overall, titanium alloy satisfies key requirements such as high strength, moderate density, controlled deformation, and low thermal expansion, making it the most structurally reliable material among the materials evaluated.

## VIII. Conclusion

The thermal mechanical comparison indicates that titanium alloy has the highest structure reliability with regards to both the mechanical loading and thermal loading. It possesses adequate safety margin where centrifugal loading is less than 120 percent and has regulated deformation pattern. Stainless steel can successfully be used at high speed with low safety margin. The alloys of aluminium, magnesium and grey cast iron do not even perform structurally at the nominal operating temperatures. The proposed methodology offers the stepwise method when it comes to selecting materials and can be extended to test high-technology alloys on-demand blades and other rotors.

## Limitations

The current research is based on the finite element simulation and is, therefore, linked to several limitations. Quantitative accuracy of the numerical results was not experimentally confirmed, and this can affect even with careful consideration of the modeling and convergence. This turbine geometrical was constructed in consultation with reference information of patents and simplified features; therefore, not all the geometric features in industry turbine blades were fully realized. The analysis did not consider internal cooling channels that are critical in the real turbine thermal management of a blade and may influence the stress distributions when it is operating. There was some steady-state assumption to test thermal loading and did not contain transient effects of cyclic heating, start-up, and start-up conditions. Moreover, the materials were all assumed to be isotropic and homogeneous also, and the real turbine materials may be anisotropic, temperature-dependent, and possess a microstructure. Regardless of these, the experiment provides a consistent comparative platform of initial material analysis and thermomechanical testing of gas turbine blades, at regular working loads.

## Future scope

### *A. Direct CAD/CAM Integration for Manufacturing*

The CAD model of the turbine blade developed in this project can be directly linked to CAD/CAM systems to generate NC (Numerical Control) codes. Using this the turbine blade design is directly used in manufacturing process, for minimizing manual work & improving accuracy during production.

### *B. Support for using advanced manufacturing methods*

The process developed in this project can help use advanced manufacturing methods such as 3D printing or hybrid techniques. These methods make it possible to create complex cooling channels, reduce weight, and improve performance—things that are hard to do with traditional manufacturing.

### *C. Material Evaluation for Different Parts*

Apart from choosing the right material for turbine blades, the same simulation method can be used to test and compare materials for other important turbine parts.

*Data Availability*
All data generated or analysed during this study are included in this published article.

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