



Research Article

Thermal and Structural Performance Analysis of YSZ-Coated Titanium Gas Turbine Blades Using ANSYS

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Abstract

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Gas turbine blades operate under severe thermal and mechanical environments, making their durability and efficiency essential for reliable aerospace and power generation applications. This study investigates the design and numerical evaluation of yttria-stabilized zirconia (YSZ) thermal barrier coatings applied on titanium alloy gas turbine blades using computer-aided design and finite element analysis. Initially, a three-dimensional turbine blade model was developed in SolidWorks, followed by structural and thermal performance assessments in ANSYS. The behavior of both coated and uncoated blade configurations was examined under applied mechanical loading and high-temperature operating conditions. Key performance parameters, including deformation, equivalent stress, elastic strain, temperature distribution, total heat flux, and directional heat flux, were analyzed to determine the influence of the YSZ coating. The simulation results demonstrated that the application of the YSZ coating improved the thermal protection capability and enhanced the overall performance of the turbine blade. The coated blade exhibited reduced thermal exposure and improved resistance against heat transfer compared with the uncoated configuration. Furthermore, the coating contributed to better stress distribution and structural stability under operating conditions. The findings confirm the potential of YSZ thermal barrier coatings as an effective approach for improving the service life, reliability, and efficiency of gas turbine components. This research provides valuable insights into simulation-based coating optimization and supports the development of advanced turbine blade technologies for high-temperature applications.

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I. INTRODUCTION

Gas turbine engines are widely utilized in sectors including aviation, electricity generation, and industrial applications due to their ability to provide high power output with efficient energy conversion. Improving the performance and extending the service life of gas turbine components, particularly turbine blades, has led to extensive research on advanced high-temperature coating technologies. These protective coatings act as a barrier between the substrate and

severe operating environments by minimizing the effects of excessive temperature exposure, oxidation, corrosion, and thermal degradation. As a result, they contribute to enhanced blade reliability and longer operational lifespan under demanding conditions. Initially, this study was intended to be conducted as an experimental investigation; however, due to practical limitations, the research approach was modified into a computational design and simulation-based study. The main aim of this research is to investigate the design and

numerical performance evaluation of high-temperature nano-coatings for gas turbine blades by employing yttria-stabilized zirconia (YSZ) as the coating material and titanium (Ti) as the substrate. These materials were selected owing to their remarkable characteristics, including high-temperature resistance, thermal stability, reduced thermal conductivity, and excellent resistance to corrosion, which make them appropriate candidates for gas turbine applications exposed to extreme operating environments.

This research aims to evaluate the performance and effectiveness of YSZ nano-coatings deposited on titanium substrates for enhancing the efficiency, durability, and operational lifetime of gas turbine blades subjected to combined thermal and mechanical loads. During the modelling stage, SolidWorks was utilized to develop a detailed three-dimensional geometry of the gas turbine blade integrated with a YSZ coating layer over the Ti substrate. The developed model enables accurate assessment of the blade geometry, dimensional features, and structural characteristics of the coated configuration. Subsequently, ANSYS finite element analysis (FEA) software was employed for numerical simulations and performance evaluation of the coated blade under different operating conditions, including high temperatures, thermal gradients, and mechanical stresses. These simulations provide an in-depth understanding of the thermal insulation effectiveness of the YSZ coating, stress distribution patterns, deformation response, and overall protective capability of the coating system. The outcomes of this study can contribute to the advancement of gas turbine materials and coating technologies by supporting the development of efficient, thermally resistant, and mechanically reliable turbine blades. Furthermore, this work establishes a connection between experimental concepts and computational modelling approaches, offering valuable insights into the future design and optimization of sustainable, high-performance gas turbine systems for aerospace and power generation applications.

The main objective of this research is to support the development of advanced nanostructured high-temperature coating systems for gas turbine blades with the aim of enhancing their operational reliability, efficiency, and service durability. The study primarily focuses on the selection of appropriate materials, where titanium (Ti) is considered as the substrate material and yttria-stabilized zirconia (YSZ) is selected as the nanocoating material due to their superior thermal and mechanical characteristics suitable for gas turbine applications. These selected materials are integrated into numerical simulation platforms to evaluate their suitability under the challenging operating conditions experienced by turbine blades. In this work, a precise three-dimensional model of a YSZ-coated gas turbine blade with a Ti substrate is developed using SolidWorks. The developed model considers the actual blade geometry and relevant design requirements associated with practical turbine blade manufacturing. The performance of the coated turbine blade is investigated through numerical simulations conducted in

ANSYS under various operating scenarios. The analyses consider the influence of high-temperature environments, thermal gradients, and mechanical loading conditions to evaluate the thermal and structural response of the blade. Based on the simulation outcomes, potential design modifications and coating optimization strategies are identified to improve blade performance and increase operational lifespan. Particular attention is given to the role of YSZ-based high-temperature coatings in minimizing the effects of oxidation, surface degradation, wear, and thermal exposure on turbine blades.

Furthermore, this research evaluates critical performance indicators related to long-term reliability, including fatigue resistance, corrosion protection, and mechanical load-bearing capability under realistic gas turbine operating conditions. The protective effectiveness of the YSZ coating in shielding the Ti substrate from oxidation, corrosion, and elevated temperatures is analyzed along with its influence on stress distribution and thermal insulation performance. In addition, the suitability of Ti and YSZ as coating-substrate materials is assessed in comparison with other potential material combinations by considering factors such as economic feasibility, material availability, and overall performance. Through these investigations, this study aims to provide valuable understanding of coating development, material selection, and simulation-based performance assessment of gas turbine blades, contributing toward the advancement of efficient and sustainable energy conversion technologies.

II. LITERATURE REVIEW

This research investigates the utilization of nanotechnology-assisted thermal barrier coatings (TBCs) for improving the performance of gas turbine blades exposed to severe thermal and mechanical environments. During operation, turbine blades experience extreme conditions, including elevated temperatures, oxidation, corrosion, thermal stresses, and erosion, which can negatively influence their structural integrity, efficiency, and service life. Therefore, the development of advanced coating solutions has become essential for enhancing blade protection, thermal resistance, and operational reliability. Recent progress in nanomaterials and thermal barrier coating technologies has shown significant potential for improving the thermal protection capability and durability of turbine components. Numerous researchers have investigated different coating materials, optimization approaches, thermal behavior, and performance enhancement strategies, which are discussed in the following sections.

Mondal *et al.* [1] investigated the growing implementation of Thermal Barrier Coatings (TBCs) in commercial and military gas turbine applications, particularly in combustion chambers and high-pressure turbine sections. Their study demonstrated that TBC systems provide effective thermal insulation, enabling turbine components to withstand higher operating temperatures while minimizing the requirement for complex cooling arrangements. The researchers identified Yttria-

Stabilized Zirconia (YSZ) as a highly suitable TBC material because of its low thermal conductivity, excellent toughness, and chemical stability. Moreover, the study highlighted the increasing adoption of TBC technologies in power generation and nuclear applications, where resistance to high temperatures and long-term durability are critical requirements.

Sankar *et al.* [2] studied the optimization of thermal barrier coating thickness for gas turbine blade applications. The study addressed an important research gap by focusing specifically on determining the optimum coating thickness while considering temperature reduction, stress control, and economic factors. Through detailed analysis and simulations, the researchers concluded that Partially Stabilized Zirconia (PSZ) is highly suitable for TBC applications because of its superior thermal insulation characteristics. The optimum coating thickness was determined to be 550 μm , which effectively balanced thermal protection, stress reduction, and cost efficiency. This research demonstrated that proper optimization of coating thickness significantly enhances turbine blade performance and operational reliability.

Li *et al.* [3] proposed an innovative methodology for optimizing the distribution of TBC thickness on gas turbine blades using finite element analysis and multi-objective optimization techniques. A detailed three-dimensional turbine blade model was developed to evaluate different coating thickness distributions. The study concluded that increasing the thickness of the top ceramic layer improved thermal insulation and reduced stress concentrations on the blade airfoil. Furthermore, the researchers proposed a three-sub-region coating distribution strategy as an effective approach for practical turbine blade design. Their work provided important insights into the development of optimized TBC architectures for improving blade durability and thermal efficiency.

Aabid *et al.* [4] carried out a heat transfer investigation using ANSYS Mechanical APDL to analyze the thermal behavior of gas turbine blades protected with different coating materials. The research concluded that the combination of Inconel 718, NiCoCrAlY, and $\text{La}_2\text{Ce}_2\text{O}_7$ coatings applied through the air plasma spraying method produced the best thermal performance. The coated blade exhibited lower temperatures and enhanced heat dissipation compared to other coating configurations. The study demonstrated that appropriate coating combinations can effectively improve thermal protection and operational efficiency in gas turbine applications.

Maktouf *et al.* [5] examined the failure mechanism of first-stage compressor blades used in gas turbine systems and identified high-cycle fatigue as the major reason behind blade failure. The investigation revealed that metallurgical imperfections located near the blade leading edge acted as initiation sites for crack formation and subsequent propagation. The authors emphasized that improved manufacturing practices, continuous vibration monitoring,

and periodic maintenance inspections are essential for reducing fatigue-related failures. Additionally, the study suggested the combined application of dynamic analysis and finite element analysis to achieve a better understanding of blade fatigue behavior under repeated thermal and mechanical loading conditions.

Zhang *et al.* [6] investigated plasma-sprayed YSZ coatings deposited using dry powder and suspension plasma spray techniques. Their research focused on analyzing coating morphology, microstructure, hardness, and thermal conductivity. The study revealed that nanostructured suspension plasma spraying eliminated undesirable monoclinic phases and improved coating adhesion and microstructural uniformity. The researchers also emphasized the significance of void structures and pseudo-columnar microstructures in improving thermal insulation performance of TBC systems.

Poojari *et al.* [7] performed a comparative evaluation of the thermal and structural behavior of gas turbine blades coated with Zirconium Carbide. Their results showed that Zirconium Carbide coatings generated lower thermal stresses and reduced heat flux compared with alternative coating materials. Moreover, the low density of this material helped preserve the lightweight design requirements of turbine blades, which is an important factor for achieving efficient turbine operation. The study concluded that Zirconium Carbide has considerable potential as an alternative coating material due to its excellent thermal resistance and mechanical strength.

Padture *et al.* [8] presented a detailed review of the development and applications of Thermal Barrier Coatings in gas turbines, aircraft engines, combustion systems, and aerospace technologies. The study highlighted that TBCs have played a significant role in improving engine efficiency and extending the service life of high-temperature components. The researchers also emphasized the need for continued investigation into coating stress development, degradation mechanisms, and advanced plasma spraying technologies to enable the production of coatings capable of operating under increasingly higher temperatures in future turbine systems.

Singh *et al.* [9] performed a comparative study of four different materials used for gas turbine blade manufacturing, including Titanium alloy, Nimonic 80A, INCONEL alloy 617, and Rhenium. Through structural and modal analyses, the researchers determined that Nimonic 80A exhibited minimum deformation and better resistance against vibration and thermal stresses. The study demonstrated that appropriate material selection is a crucial factor in achieving enhanced blade reliability, mechanical stability, and safe operation under extreme service conditions. A finite element analysis investigation of gas turbine rotor blades reported that temperature variations have a significant influence on blade elongation, stress distribution, and strain behavior. The analysis showed that the highest temperature and maximum

elongation occurred at the blade tip, whereas the root region experienced the greatest stress concentration [10]. Among the investigated materials, Inconel 625 exhibited better thermal characteristics and lower thermal stress levels, indicating its suitability for high-temperature gas turbine blade applications. Another finite element analysis study on gas turbine rotor blades concluded that temperature significantly influences blade elongation, stress distribution, and strain behavior. The analysis revealed that the blade tip experienced maximum temperatures and elongation, while the root section exhibited maximum stresses [10]. Among the evaluated materials, Inconel 625 demonstrated superior thermal properties and reduced thermal stresses, making it highly suitable for gas turbine blade applications.

Ghasemi *et al.* [11] studied plasma-sprayed YSZ coatings produced through conventional dry powder spraying and suspension plasma spray techniques. The researchers reported that suspension plasma-sprayed coatings demonstrated improved thermal behavior and greater resistance to thermally induced strains due to the development of pseudo-columnar microstructures. Their findings highlighted that controlled microstructural features and optimized void structures within the coating significantly influence the thermal insulation capability and overall performance of thermal barrier coatings.

Raga *et al.* [12] investigated the design and development of first-stage rotor blades for open-cycle gas turbine power generation systems. The researchers utilized SolidWorks and MATLAB to generate accurate blade geometries and assess the proposed designs through numerical simulations and analytical validation. The obtained results verified the accuracy, reliability, and effectiveness of the developed blade design approach.

Teja *et al.* [13] conducted a numerical investigation of graphite, titanium, and zirconium alloys for gas turbine blade applications. The analysis revealed that titanium alloy exhibited comparatively lower stress, strain, and deformation values than the other selected materials. In addition, titanium demonstrated favorable modal characteristics and reduced thermal conductivity, indicating its suitability for turbine blades subjected to combined thermal and mechanical loading conditions.

Xu *et al.* [14] investigated Thermal Barrier Coatings fabricated using the Electron Beam-Physical Vapor Deposition (EB-PVD) technique. The study revealed that thermal cycling primarily initiated cracks at the ceramic and oxide interface regions. Furthermore, increasing the thickness of the ceramic top layer enhanced the thermal barrier capability by increasing the temperature difference across the coating system. The researchers emphasized that appropriate selection of coating materials and optimization of coating thickness are essential factors for improving the durability and thermal performance of TBC systems.

Overall, the reviewed studies demonstrate the significant contribution of nanotechnology-based Thermal Barrier Coatings, particularly YSZ-based systems, toward improving the thermal protection, durability, and efficiency of gas turbine blades. Previous research has extensively explored different aspects, including coating thickness optimization, microstructural enhancement, thermal and mechanical performance evaluation, and selection of suitable substrate-coating combinations. However, further investigation is still required to integrate nanotechnology approaches with advanced coating development strategies and simulation-driven optimization methods for improving turbine blade performance under extreme operating environments. Therefore, the present study aims to address this research gap by evaluating nanotechnology-based high-temperature coating systems for gas turbine blades through advanced modelling and simulation techniques.

III. METHODOLOGY

A flow chart explaining the step-by-step pathway of the research is as follows:

The research methodology was initiated with a comprehensive review of existing studies related to gas turbine blade technologies, material selection, coating systems, and design methodologies. The main objective of this review was to establish an in-depth understanding of the approaches used for designing turbine blades capable of operating under extremely high temperatures and severe service conditions encountered in gas turbine engines. Relevant information was gathered from scientific journals, research publications, technical reports, patents, and other reliable sources to develop a detailed understanding of current developments, limitations, and challenges associated with turbine blade technologies. During the literature investigation, various coating materials, thermal barrier coating systems, blade configurations, and manufacturing techniques reported in previous studies were critically examined to assess their influence on blade performance, thermal protection capability, and long-term durability. This systematic evaluation provided valuable insights into the limitations of existing turbine blade materials and coating technologies, which helped define the direction of the present research. Based on the findings obtained from the literature analysis, the study was further advanced toward simulation-based design and computational investigations aimed at addressing the identified challenges and improving turbine blade performance. The subsequent research activities involved three-dimensional modelling, numerical simulation, and analytical evaluation to investigate potential strategies for enhancing thermal stability, operational reliability, and service life of gas turbine blades. These approaches were employed to explore improved design concepts and contribute toward the development of advanced gas turbine blade technologies.

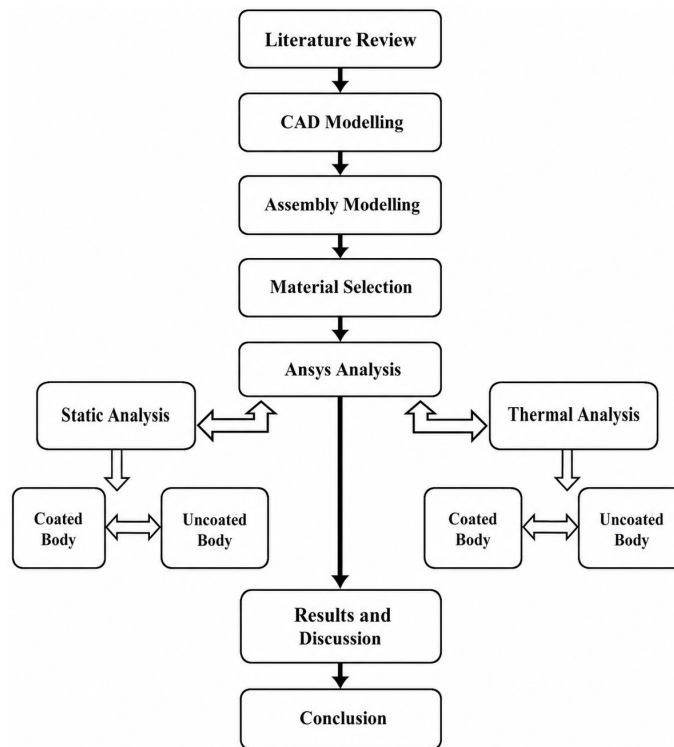


Fig.1 Methodological Flow Diagram

A. Model Specifications

The geometric specifications of a gas turbine blade represent the basic structural and dimensional parameters required for accurate modelling, design evaluation, and performance analysis. These specifications are determined by considering several critical aspects, including material characteristics, aerodynamic behavior, cooling requirements, thermal resistance, and structural stability, to ensure reliable operation under the severe conditions experienced inside gas turbine engines. Gas turbine blades are among the most important components influencing the efficiency, reliability, and service performance of turbine systems used in aerospace, power generation, and industrial sectors. Their primary role is to extract energy from high-temperature, high-speed combustion gases and transform it into mechanical rotational energy through the turbine assembly. Because turbine blades are subjected to intense thermal and mechanical loading during operation, they require materials with excellent strength, temperature resistance, and durability. Therefore, advanced materials such as nickel-based superalloys, titanium alloys, and ceramic-based materials are commonly considered for turbine blade applications due to their favorable thermal and mechanical characteristics.

The designed gas turbine blade in this research has an overall length of 120 mm, measured from the root to the tip of the blade. The actual blade section length is 100 mm, which mainly contributes to aerodynamic performance and energy extraction from the flowing gases. The remaining 20 mm consists of the root section, which is responsible for securely connecting the blade to the rotor hub. The root section is

generally thicker than the blade body to provide sufficient mechanical strength and stability during high speed rotation. It often includes a dovetail or similar attachment mechanism to ensure a strong and reliable connection between the blade and the rotor assembly. These geometric specifications are important for achieving proper structural support, efficient thermal performance, and enhanced operational reliability of the gas turbine blade under extreme working conditions.

B. Material Composition

In this research, titanium is selected as the substrate material for the gas turbine blade due to its desirable mechanical and thermal properties. Titanium alloys are extensively considered for turbine applications because of their high strength-to-weight ratio, excellent corrosion resistance, and ability to maintain performance under elevated temperatures and mechanical loading conditions. To improve the thermal protection capability and extend the operational durability of the blade, a yttria-stabilized zirconia (YSZ) coating layer is applied to the surface of the titanium substrate. YSZ is one of the most widely used ceramic materials for thermal barrier coating (TBC) applications in gas turbine systems because of its low thermal conductivity, high-temperature stability, and effective resistance against thermal degradation. In this study, the YSZ coating applied has a thickness of 0.3 mm, which serves to protect the titanium substrate from excessive heat exposure and minimize heat transfer into the blade during operation. This thermal barrier significantly improves the blade's lifespan, efficiency, and resistance to thermal degradation. In addition to the material specifications and coating thickness, the blade profile and cross-sectional geometry are also important design considerations. The

airfoil shape and dimensions of the blade directly influence its aerodynamic performance, airflow characteristics, energy extraction efficiency, and overall operational stability within the gas turbine engine. Therefore, careful attention is given

to the blade's profile to achieve optimal thermal and aerodynamic performance under high temperature operating conditions.

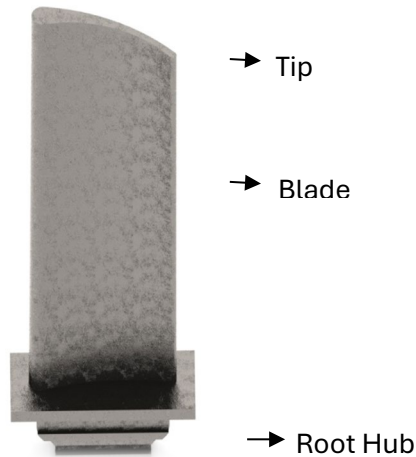


Fig.2 Gas Turbine Blades

C. Software Selection

For the design, simulation, and analysis of the gas turbine blade and coating system, SolidWorks and ANSYS software were selected based on standard engineering industry practices. SolidWorks was used for computer-aided design (CAD) modelling due to its user-friendly interface, parametric modelling capabilities, and efficiency in creating accurate three-dimensional models and assemblies. In this research, SolidWorks was utilized to design the gas turbine blade and the YSZ coating individually before combining them into a complete assembly model. This modular design approach enabled detailed examination of each component and ensured precise integration of the coating with the blade structure. The software also facilitated accurate modelling of the blade geometry, dimensions, and structural features required for further analysis. ANSYS was employed for simulation and analysis because of its advanced finite element analysis (FEA) capabilities. The software was mainly used to perform thermal and static analyses of the coated gas turbine blade. Thermal analysis was conducted to evaluate heat distribution, temperature gradients, and thermal stresses within the blade and coating under high-temperature operating conditions, while static analysis was performed to investigate the mechanical stresses, deformation behavior, and structural stability of the blade under applied loads. The combined use of SolidWorks and ANSYS provided a comprehensive understanding of the coated gas turbine blade's performance under realistic operational conditions and helped optimize the design for improved efficiency, thermal resistance, durability, and structural reliability.

D. Design of Gas Turbine Blade Using SOLIDWORKS

The three-dimensional design of the gas turbine blade was developed using SolidWorks software. Initially, a new part

document was created by selecting the “File > New > Part” option. After establishing the part environment, the modelling units were adjusted to millimeters through the “Tools > Options > Document Properties > Units” settings to maintain dimensional consistency throughout the design process. The modelling procedure started with the development of the blade root section. The front plane was selected as the initial sketching surface, and the root section dimension was defined with a length of 20 mm. A two-dimensional profile of the root geometry was then generated using the available Sketch tools. The root region represents the connecting section between the turbine blade and rotor hub, providing the necessary mechanical support and stability during high-speed turbine operation. Different sketching features were applied to obtain the required root geometry according to the design specifications. After finalizing the sketch, the Extrude feature was applied to extend the root profile by 20 mm in the specified direction.

Furthermore, the Extrude Cut feature was employed to introduce grooves or striped patterns within the lower blade body as required by the proposed design. Following the root section design, the blade tip and airfoil profile were developed. A top plane was created above the root section to facilitate the blade profile design. Different sketching commands and a specified angle of 135° were used to generate the blade geometry, while the blade profile length was maintained at 100 mm. To achieve the smooth aerodynamic shape of the turbine blade, a new plane and blade surface were generated using the Loft command. This approach enabled the creation of a precise three-dimensional gas turbine blade model suitable for further thermal and structural analysis in ANSYS.



Fig.3 Gas Turbine Blade Model

1. Creation of Coating for Surface: For the development of the coating model, Sketch 4 from the blade profile created using the Loft command was copied and transferred into a newly opened part file in SolidWorks. After creating the new part, an additional plane was generated at a distance of 100 mm, where Sketch 5 copied from the previous Loft geometry was pasted. Both sketch components were carefully rearranged and aligned at the center to ensure proper positioning and geometric accuracy of the coating structure. To generate the coating surface, the Surface Loft command was applied between the two sketches, creating a smooth aerodynamic surface corresponding to the blade profile. After the surface generation, the Thicken command was used to provide the coating layer with a thickness of 0.3 mm, representing the YSZ thermal barrier coating applied over the turbine blade surface. The final coating surface was designed with a dimension of 100 mm, matching the blade profile length. This modelling approach enabled the creation of an accurate coating geometry suitable for further thermal and structural simulations in ANSYS.



Fig.4 Surface for the Coating Body

2. Assembly: After separately developing the gas turbine blade and YSZ coating models, both components were combined to create the complete coated blade assembly in SolidWorks.

Initially, an assembly file was created by opening SolidWorks and selecting the “Assembly” option as the required document type. Using the “Insert Components” command, both the turbine blade part and the coating model were imported into the assembly environment. Following the insertion of the components, proper mating and alignment operations were performed to accurately position the coating over the turbine blade surface. Both components were aligned parallel to each other to ensure correct placement and geometric consistency. For precise alignment, entity points were created on Sketch 4 and Sketch 5, as well as on the edge of the turbine blade. These entity points served as reference locations for the mating process. The “Mate” command was then used to align and join the corresponding entity points, resulting in the accurate placement of the coating layer onto the turbine blade surface. This assembly process produced a complete coated gas turbine blade model suitable for further thermal and structural analysis in ANSYS.

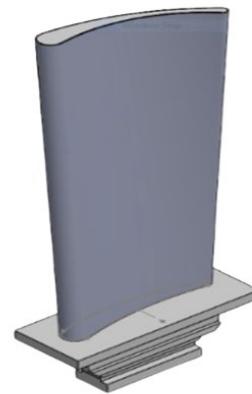


Fig.5 Coated Assembly

3. Rendering of Model: Rendering refers to the process of converting three-dimensional models into realistic visual representations by applying appropriate lighting, material properties, textures, and viewing conditions. In this research, rendering was performed in SolidWorks to create detailed and realistic images of the coated gas turbine blade model. The rendering process involved simulating lighting conditions, material appearances, textures, and camera perspectives to produce high-quality visual outputs of the designed assembly.

Initially, the completed gas turbine blade assembly was opened in SolidWorks for rendering purposes. After opening the model, the scene and environment settings were configured by adjusting the background, lighting conditions, and camera angles to achieve the desired visual appearance and realistic presentation. Material appearances and textures were then applied to the assembly components, where metallic material properties and titanium soft textures were assigned to accurately represent the turbine blade surface characteristics.

Following this, camera settings such as viewing angle, field of view, and depth of field were adjusted to properly frame the model and obtain the required perspective. The rendering parameters were configured through the Render Tools tab in SolidWorks, where Photoview 360 was selected as the rendering mode along with the default quality and resolution settings. Finally, the rendering process was initiated by clicking the render command, which generated the final rendered image of the coated gas turbine blade assembly.

The rendered output was then saved in the desired file format and location for further analysis, presentation, and documentation purposes.

4. Drawing of the Model: The engineering drawings of the gas turbine blade and coating models developed in SolidWorks are presented below. These drawings illustrate the geometrical details, dimensions, and design features of the developed model used for further simulation and analysis.

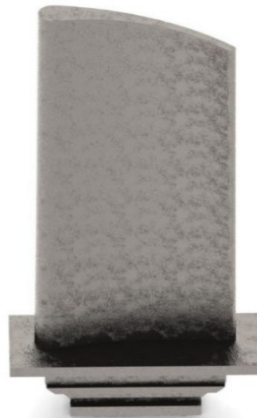


Fig.6 Rendered Image

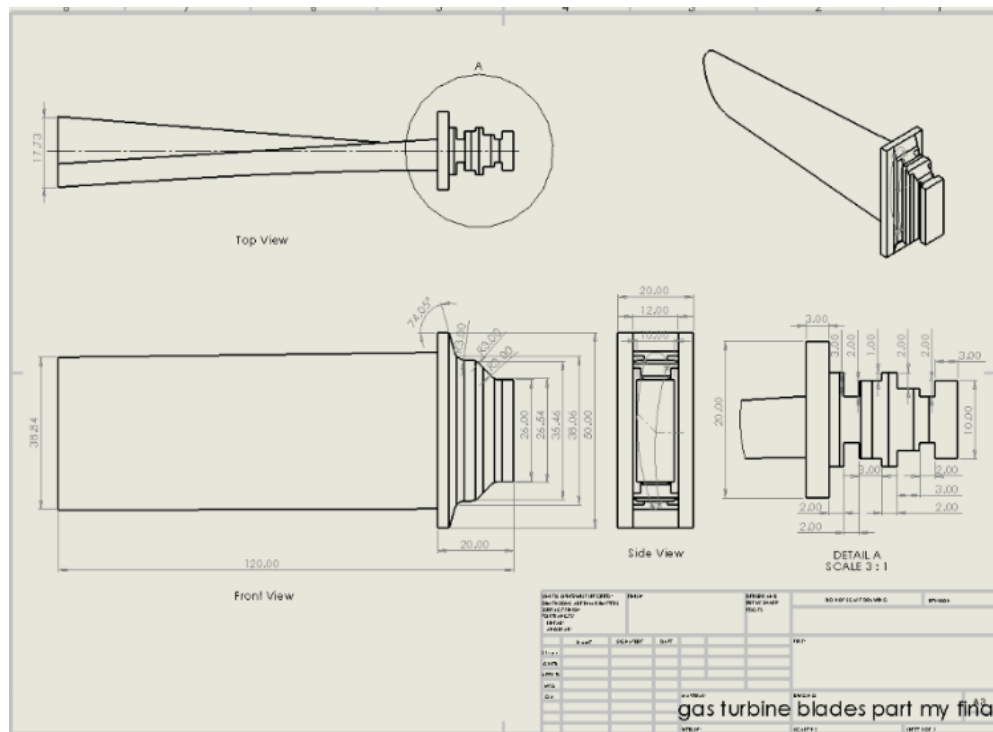


Fig.7 Drawing of the Model

5. Material Selection: The selection of suitable materials for gas turbine blades requires careful consideration of various performance parameters, including thermal stability, mechanical strength, density, durability, and resistance to oxidation and corrosion. Since turbine blades operate under extremely high temperatures and mechanical loading

conditions, the selected materials must possess sufficient capability to maintain their structural and functional performance throughout service operation. Therefore, engineers typically evaluate and compare different materials based on their thermal and mechanical characteristics to achieve optimum performance for specific gas turbine

applications. In this research, titanium alloy was selected as the substrate material, while yttria-stabilized zirconia (YSZ) was chosen as the thermal barrier coating material due to their suitable properties for high-temperature turbine blade applications. Titanium alloys, particularly Ti-6Al-4V, are extensively employed in aerospace and gas turbine components because of their excellent strength-to-weight ratio, corrosion resistance, and favorable thermal stability. The density of titanium alloy is approximately 4.6×10^{-6} kg/mm³, which contributes to reducing the overall weight of turbine components. The material exhibits a Young's modulus of approximately 96,000 MPa, demonstrating its ability to resist elastic deformation under applied mechanical loads. Furthermore, titanium alloy possesses a yield strength of approximately 930 MPa and an ultimate tensile strength of nearly 1070 MPa, allowing it to withstand considerable mechanical stresses before failure. Regarding thermal characteristics, titanium alloy has a thermal conductivity of approximately 0.0219 W/(mm·°C), providing moderate heat transfer capability, while its specific heat capacity at room temperature is approximately 5.22×10^{-5} mJ/Kg.

Additionally, the coefficient of thermal expansion (CTE) of titanium alloy is around 9.4×10^{-6} /°C, which contributes to its ability to maintain dimensional stability under temperature variations. For the coating layer, yttria-stabilized zirconia (YSZ) was selected because of its outstanding thermal insulation properties and capability to withstand high-temperature environments. YSZ is a ceramic-based material widely utilized as a thermal barrier coating (TBC) in aerospace propulsion systems and power generation applications. The density of YSZ is approximately 5850 kg/m³, while its Young's modulus is around 210 GPa, indicating high stiffness and structural stability. The material has a Poisson's ratio of approximately 0.21, representing its elastic response under mechanical loading. Due to the brittle characteristics of ceramic materials, YSZ does not exhibit a distinct yield strength; however, it possesses an ultimate tensile strength greater than 200 MPa and a compressive strength exceeding 1000 MPa, enabling it to withstand substantial compressive forces.

YSZ also exhibits high hardness, ranging from 11 to 13 GPa on the Vickers hardness scale, which provides excellent resistance against surface wear and mechanical damage. One of the most important characteristics of YSZ is its low thermal conductivity, approximately 2.12 W/(m·K), which enables effective reduction of heat transfer from the combustion environment toward the underlying substrate. The specific heat capacity of YSZ is approximately 0.51 J/(g·K), while its coefficient of thermal expansion is around 1.07×10^{-5} /°C, helping to minimize thermal mismatch stresses between the coating and titanium substrate.

Moreover, YSZ has a very high melting temperature above 2700°C, allowing it to retain its structural stability under extreme thermal conditions. Due to its combination of thermal insulation capability, mechanical stability, and high-temperature resistance, YSZ is considered an effective thermal barrier coating material for improving the durability, reliability, and performance of gas turbine blades operating in severe environments.

IV. MODEL ANALYSIS

Model analysis in ANSYS consists of importing a three-dimensional CAD geometry, assigning material properties, applying suitable boundary conditions and loading conditions, generating a finite element mesh, and performing numerical simulations to evaluate the physical response of the designed model. These computational analyses allow the investigation of important engineering parameters, including stress distribution, deformation behavior, temperature variation, and other performance characteristics under specified operating conditions. In this study, static structural analysis and steady-state thermal analysis were performed for both coated and uncoated gas turbine blade configurations. The results obtained from these analyses were compared to determine the influence and effectiveness of the YSZ coating in improving the blade's thermal and structural performance. The static structural analysis was conducted to evaluate the mechanical response of the gas turbine blade under applied loading conditions, including centrifugal forces and thermally induced stresses. By incorporating the defined boundary conditions and material properties of both the titanium substrate and YSZ coating layer, the analysis enabled the investigation of deformation patterns, stress distribution, and critical regions susceptible to failure. The obtained results provided valuable information regarding the structural integrity, mechanical reliability, and durability of the blade under simulated operating conditions. Furthermore, the analysis supported the identification of potential design improvements and contributed to enhancing the safety and performance of gas turbine blade systems.

A. Geometry Import

The three-dimensional geometry of the gas turbine blade model, which was originally developed in SolidWorks, was imported into ANSYS for further analysis. After importing the model, it was generated and prepared for simulation using the F5 command within the ANSYS environment. To ensure consistency and accuracy in calculations, all units were converted to the metric system (millimeter–kilogram), aligning the model with standard engineering unit conventions used in the analysis process.

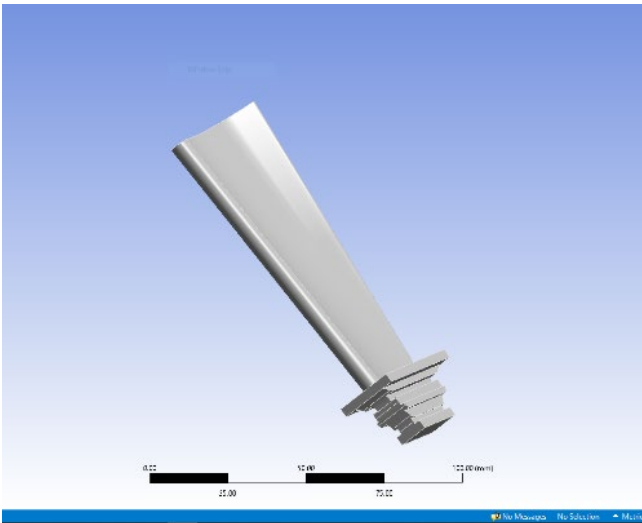


Fig.8 Geometry

Engineering Data Material View	
Q Enter name, label, property	
★ Welded Joint	
★ Structural Steel	
★ Air	
★ Titanium Alloy	
Titanium Alloy	
Density	4.42e-06 kg/mm³
Structural	
Viscoelastic Elasticity	
Define from	Window Say
Young's Modulus and Poisson's Ratio	
Young's Modulus	96000 MPa
Poisson's Ratio	0.36
Bulk Modulus	1.429e+05 MPa
Shear Modulus	35294 MPa
Isotropic Secant Coefficient of Thermal Expansion	9.4e-06 1/°C
Compressive Ultimate Strength	0 MPa
Compressive Yield Strength	930 MPa
Tensile Ultimate Strength	1320 MPa
Tensile Yield Strength	930 MPa
Thermal	
Isotropic Thermal Conductivity	0.0229 W/mm-°C
Specific Heat Constant Pressure	5.22e-05 mJ/kg-°C
Electric	
Isotropic Resistivity	0.0017 ohm-mm
Magnetic	
Isotropic Relative Permeability	1

Fig.9 Properties of Selected Titanium Alloy (substrate)

B. Material Selection

For the gas turbine blade model illustrated above, titanium alloy was assigned as the substrate material through the Engineering Data module in ANSYS. The corresponding material properties of the selected titanium alloy are presented in Figure 9.

C. Mesh Generation

A finite element mesh was generated for the gas turbine blade model to discretize the geometry into a large number of small

elements, enabling numerical analysis. The element size was defined as 0.4 mm, and ANSYS was allowed to automatically perform the meshing process for accurate simulation results. The mesh resolution settings were kept at the default values, with no additional modifications made to the refinement parameters. A fine and fast meshing option was selected, which produced a high-quality mesh suitable for reliable analysis. The resulting mesh ensured proper representation of the blade geometry and provided sufficient accuracy for subsequent static structural and thermal simulations, as shown in Figure 10.

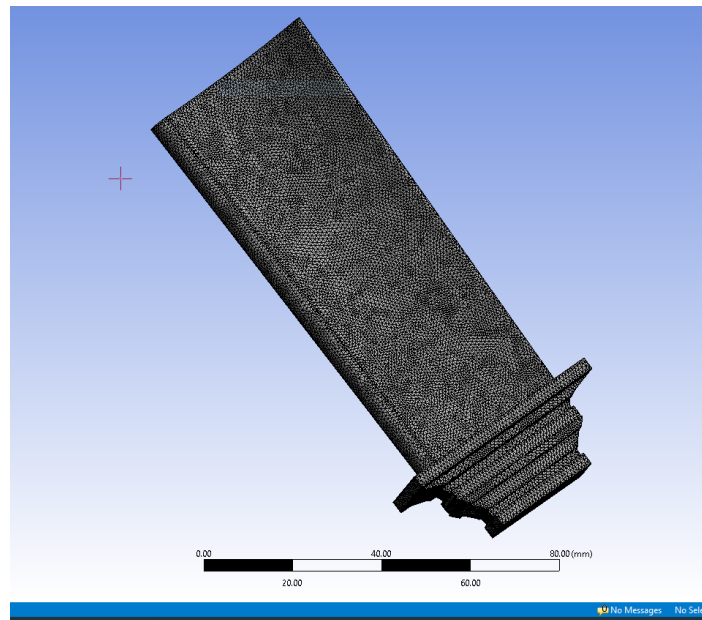


Fig.10 Mesh

D. Boundary Conditions

The first boundary condition applied in the analysis was a fixed support condition. The faces at the root section of the gas turbine blade were selected and constrained, as shown in the figure below, to simulate the rigid attachment of the blade to the rotor hub and to restrict all degrees of freedom at the support region. In addition to this, a rotational velocity

boundary condition was applied to the entire blade body to represent real operating conditions of the turbine. A rotational speed of 785.4 rad/sec was assigned about the x-axis, ensuring that the centrifugal effects acting on the blade during rotation were properly included in the simulation. These boundary conditions collectively enabled a realistic representation of the blade's working environment for accurate structural analysis.

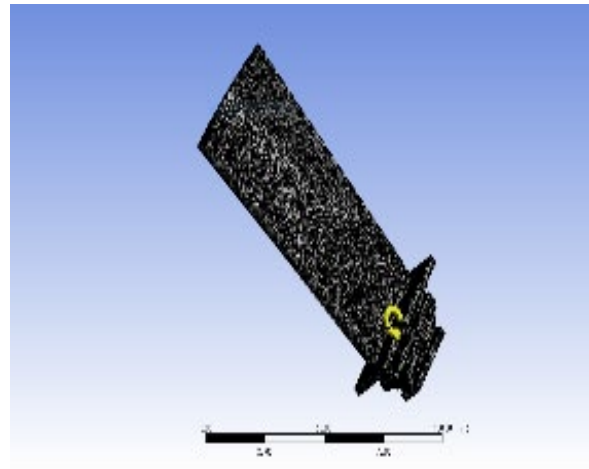
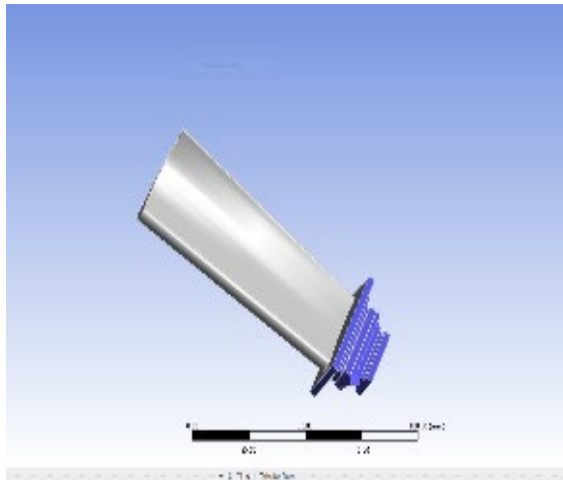


Fig.11 (a) Fixed Support; (b) Rotational Velocity

E. Solver Setup, Analysis Desired and Post-Processing

The analysis was configured in ANSYS Mechanical by selecting the “Static Structural” analysis type, as the objective of this research was to evaluate the static behavior of the gas turbine blade under applied loading conditions. This setup enabled the investigation of structural responses such as stress distribution, deformation, and strain within the blade during operation. The solver settings were maintained at their default values to ensure stable and efficient computation throughout the simulation process. The analyses

conducted in this research included total deformation, equivalent elastic strain, and equivalent stress evaluations of the gas turbine blade under applied loading conditions. These analyses were performed to assess the deformation behavior, strain distribution, stress concentration, and overall structural integrity of both coated and uncoated turbine blade models during operation. The required analyses were executed in ANSYS, and various post-processing tools available within the software were used to obtain results related to stress distribution, total deformation, and elastic strain of the gas turbine blade.

F. Deformation

Deformation analysis was performed to evaluate the change in shape and displacement behavior of the blade under the applied loading conditions. The results show that the minimum deformation value was 0 mm at the root section of

the blade due to the fixed support condition, while the maximum deformation observed was 0.556 mm at the upper tip of the blade. This deformation pattern demonstrates that the blade tip experiences the highest displacement during operation, whereas the root section remains fully constrained and stable.

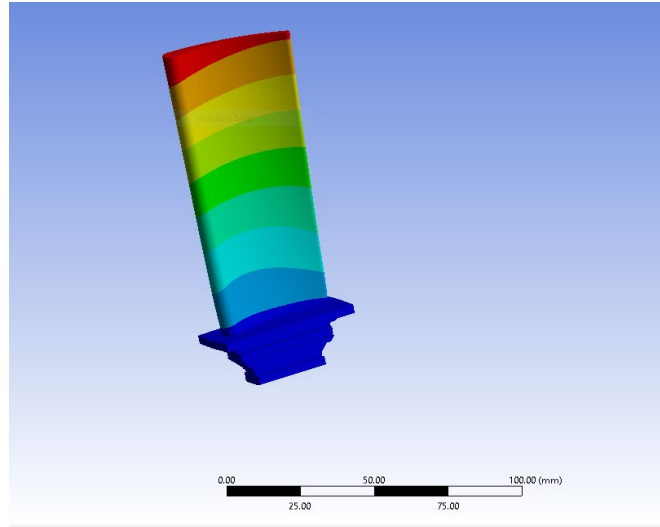


Fig.12 Deformation

G. Equivalent Elastic Strain

Equivalent elastic strain analysis was performed to evaluate the elastic deformation behavior of the gas turbine blade

under applied loads. The results showed a maximum equivalent elastic strain of 0.0147 mm/mm at the root section of the blade, while the minimum value observed was 2.843×10^{-15} mm/mm.

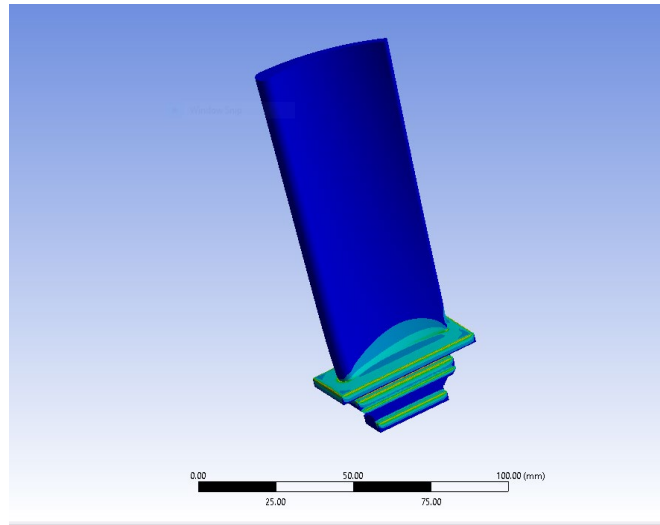


Fig.13 Equivalent Elastic Strain

H. Equivalent Stress

Equivalent stress analysis was performed to evaluate the combined effect of stresses acting on the gas turbine blade under static loading conditions. The results indicated that the minimum equivalent stress value was 0 MPa, while the maximum stress recorded was 1336.6 MPa. The highest

stress concentration was observed mainly at the root section of the blade, with slight stress distribution also appearing along the blade edge. These results indicate that the root region experiences the greatest mechanical loading and is the most critical area in terms of structural integrity and potential failure.

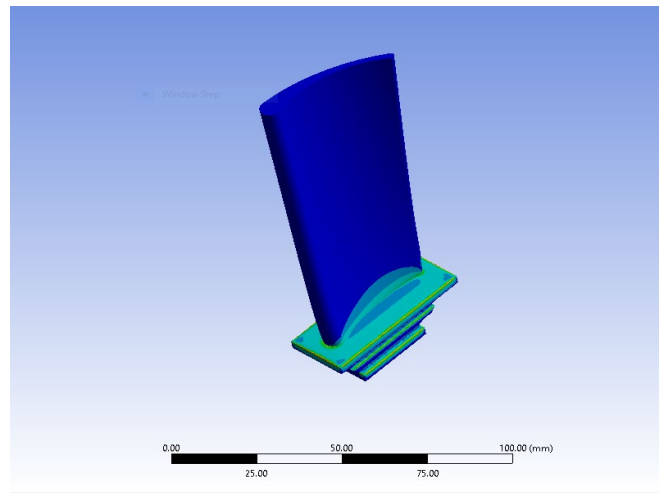


Fig.14 Equivalent stress

V. STATIC STRUCTURAL EVALUATION OF A YSZ-COATED GAS TURBINE BLADE

The static structural analysis of the coated gas turbine blade was performed to evaluate the influence of mechanical loading conditions, including centrifugal forces and thermally induced stresses, on blade deformation behavior and structural response. Through this, an evaluation of blade deformation, stress, and possible points of failure was done to ensure blade reliability and efficiency. Static structural analysis was intended to help improve design and guarantee safety of gas turbine engines. Below is a step-by-step process of the analysis:

A. Geometry Import

The three-dimensional CAD model of the coated gas turbine blade assembly, developed in SolidWorks, was transferred into the ANSYS environment for subsequent numerical simulation and performance analysis. After importing the assembly model, the geometry was generated and prepared using the F5 command within the ANSYS environment. To maintain consistency and accuracy throughout the analysis process, all units were converted to the metric system (millimeter–kilogram).

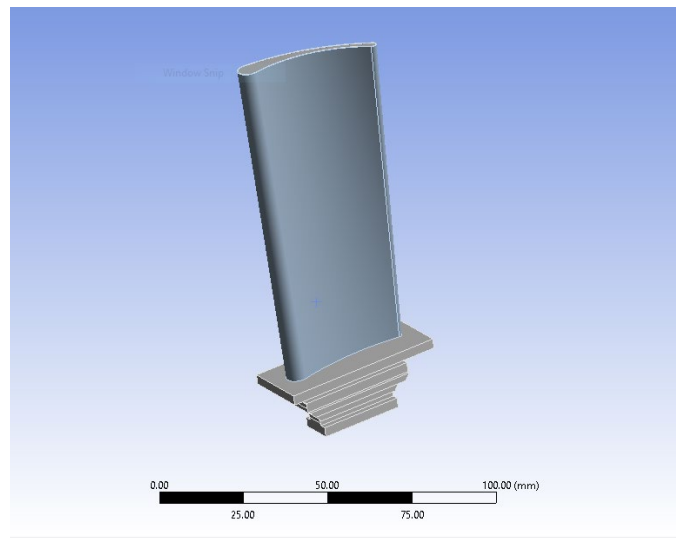


Fig.15 Geometry

B. Material Selection

For the above design of the gas turbine blade, titanium alloy was assigned as the substrate material through the Engineering Data module in ANSYS. The coating layer was defined using yttria-stabilized zirconia (YSZ), and its

required material properties were incorporated into the ANSYS database for simulation purposes. The corresponding material properties of both the YSZ coating and titanium alloy substrate are provided in the following tables.

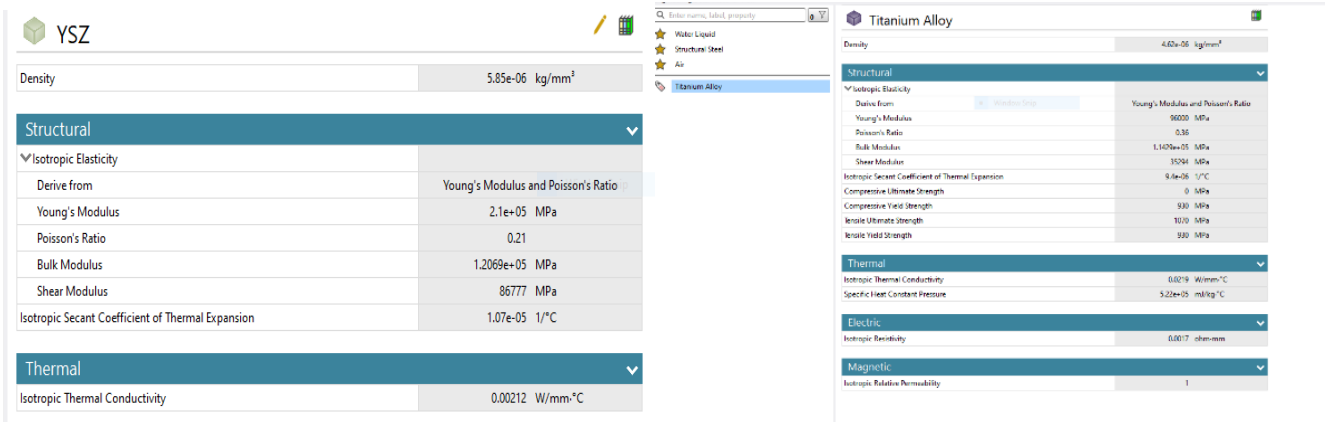


Fig.16 (a) Properties of YSZ; (b) Properties of Titanium Alloy (substrate)

C. Mesh Generation

A finite element mesh was generated for the coated gas turbine blade model to divide the geometry into small elements for numerical analysis. The element size was selected as 0.4 mm, and ANSYS was allowed to automatically perform the meshing process. The mesh resolution settings were kept at their default values without any additional modifications. A fine and fast meshing option was selected, resulting in a high-quality mesh consisting of 347,177 nodes and 196,294 elements, as shown in Figure 17. This mesh quality ensured accurate and reliable results for the subsequent structural and thermal analyses of the coated gas turbine blade.

D. Boundary Conditions

The initial boundary condition applied in the analysis was a fixed support constraint. The faces located at the root section of the turbine blade were selected and restricted to prevent any displacement during the simulation, as illustrated in the figure below, to simulate rigid attachment to the rotor hub. In addition to this, a rotational velocity of 785.4 rad/sec was applied to the entire coated blade body to represent real operating conditions and to account for centrifugal effects during operation. The rotational motion was defined about the x-axis of the component to ensure correct directional loading. These boundary conditions together provided a realistic simulation environment for analyzing the structural behavior of the coated gas turbine blade under service conditions.



Fig.17 Mesh

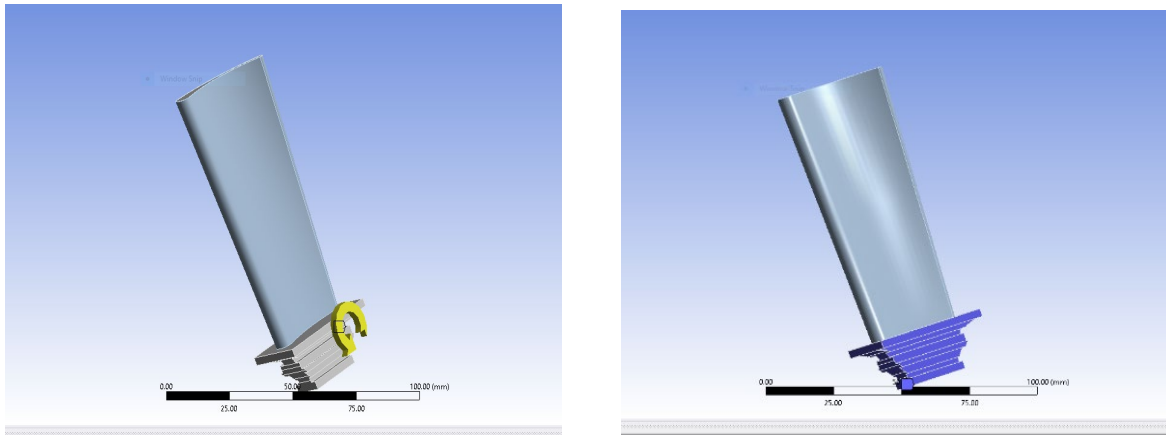


Fig.18 (a) Fixed Support; (b) Rotational Velocity

E. Solver Setup, Analysis Desired and Post-Processing

The analysis was set up in ANSYS Mechanical by selecting the “Static Structural” analysis type, as the study focused on evaluating the static behavior of the coated gas turbine blade under applied loading conditions. This setup enabled the assessment of structural responses such as stress distribution, deformation, and strain within the model. The solver settings were kept at their default configuration to ensure stable and efficient computation during the simulation process. The desired analyses included total deformation, equivalent elastic strain, and equivalent stress. The analyses were performed using ANSYS, and with the use of different post-processing features of ANSYS, stress distribution, total deformation, and elastic strain were determined.

F. Deformation

Deformation represents the alteration in the original geometry or the displacement experienced by a component when subjected to external loading conditions, typically expressed in terms of strain or displacement distribution. The deformation analysis of the coated gas turbine blade was carried out to evaluate its structural response during operation. The results indicated that the minimum deformation was 0 mm at the root section of the blade due to the fixed support condition, while the maximum deformation observed was 0.683 mm at the upper tip of the blade. This indicates that the highest displacement occurs at the blade tip, whereas the root remains fully constrained and experiences no movement.

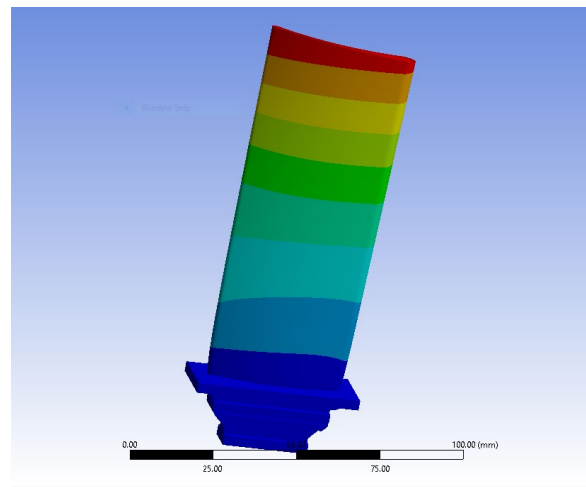


Fig.19 Deformation

G. Equivalent Elastic Strain

Equivalent elastic strain describes the overall elastic deformation behavior of a material under applied loading by converting complex strain components into a single representative scalar value. In this study, equivalent elastic strain analysis was conducted for the coated gas turbine blade to assess its elastic deformation characteristics under the applied operating conditions. The simulation results

indicated that the maximum equivalent elastic strain value obtained for the coated blade was 0.0143 mm/mm, which occurred at the root section of the blade due to stress concentration at the fixed support, while the minimum equivalent elastic strain was 0 mm/mm in regions with negligible deformation. This indicates that the highest elastic deformation is localized at the blade root, whereas minimal strain is observed in other areas of the blade.

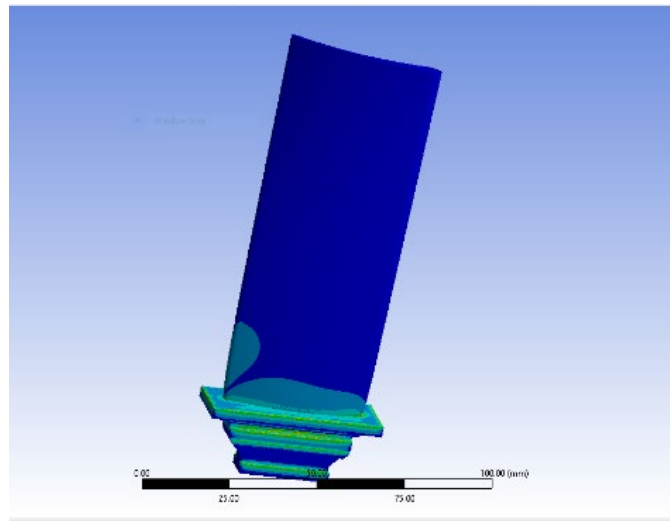


Fig.20 Equivalent Elastic Strain

H. Equivalent Stress

Equivalent stress in static structural engineering is a measure that gives a single value for the effect of several stress states. This makes it easy to analyze stress distribution in materials and identify any failure points of the material. The following

graph indicates the value of stress caused by the gas turbine blade. The stress analysis results indicated that the minimum stress value generated within the coated gas turbine blade was 0.0394 MPa, while the maximum recorded stress reached 1122.1 MPa under the applied loading conditions.

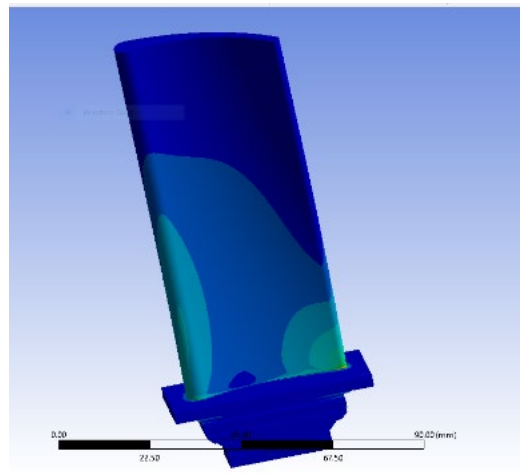


Fig.21 Equivalent Stress

VI. STEADY-STATE THERMAL ANALYSIS ON GAS TURBINE BLADE

Steady-state thermal analysis in ANSYS is a simulation approach that focuses on studying temperature distribution within a system where thermal equilibrium is achieved. In other words, it is a simulation process that determines how the temperature fields of a system are affected by various thermal loads and boundary conditions. Steady-state thermal analysis in ANSYS is an effective computational approach for evaluating the temperature behavior and thermal performance of engineering components where maintaining thermal stability is critical. In the case of gas turbine blades, steady-state thermal analysis is used to investigate the response of the blade under constant thermal loading conditions and to determine the temperature distribution after

reaching thermal equilibrium. Since turbine blades operate in extremely high-temperature environments generated by fuel combustion, it is essential to evaluate their ability to withstand thermal exposure and maintain structural integrity. This analysis provides valuable information regarding heat transfer characteristics, temperature variations, and the thermal performance of gas turbine blade systems under operating conditions. The following section presents the steady-state thermal analysis procedure of the gas turbine blade performed in ANSYS.

A. Geometry

The three-dimensional model of the gas turbine blade along with its associated surrounding components was developed in SolidWorks, as can be seen in the following figure:

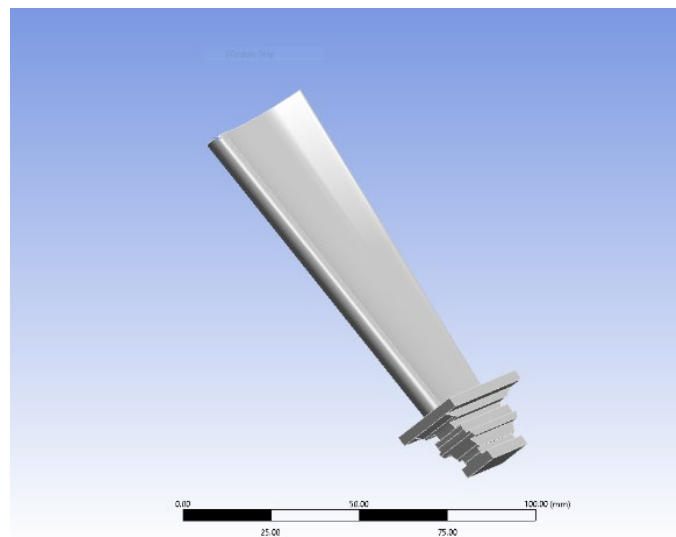


Fig.22 Geometry

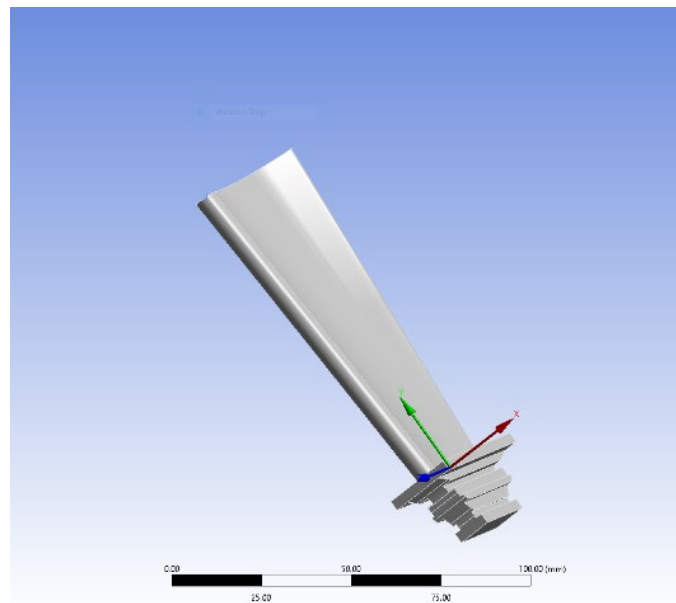


Fig.23 Coordinate System

B. Coordinate System

A graphical representation of the established coordinate system used for the analysis is presented below.

C. Mesh Generation

A mesh for the gas turbine blade model was created. After that, it was used to divide the model into small elements; their size was selected to be 0.4 mm, and numerical analysis was carried out using ANSYS software.

The default mesh resolution was used, and no changes were made. The selected mesh type was fine and fast, and the mesh

quality turned out to be very good, as can be seen in the figure below.

D. Boundary Conditions

The thermal boundary conditions were defined by applying two different temperature constraints: root temperature and blade surface temperature. A root temperature of 250°C was assigned to the selected 47 faces at the blade root section. In addition, a blade surface temperature of 500°C was applied to the designated blade face region, as illustrated in Figure 25. These thermal boundary conditions were established to simulate the temperature distribution experienced by the gas turbine blade during high-temperature operating conditions.

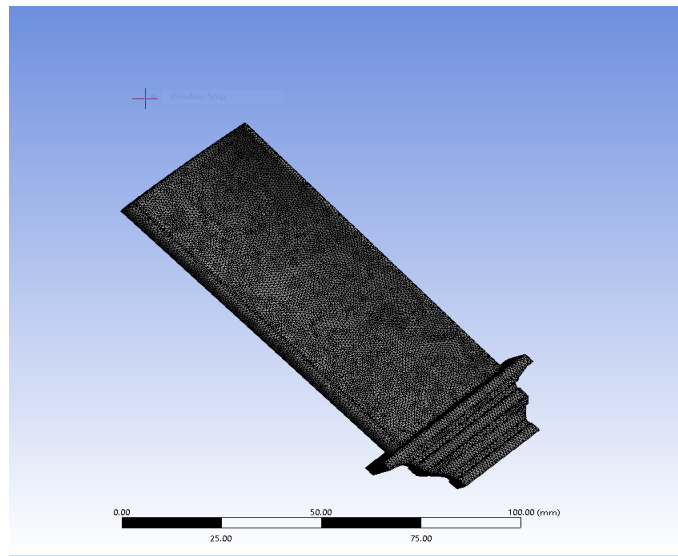


Fig.24 Mesh

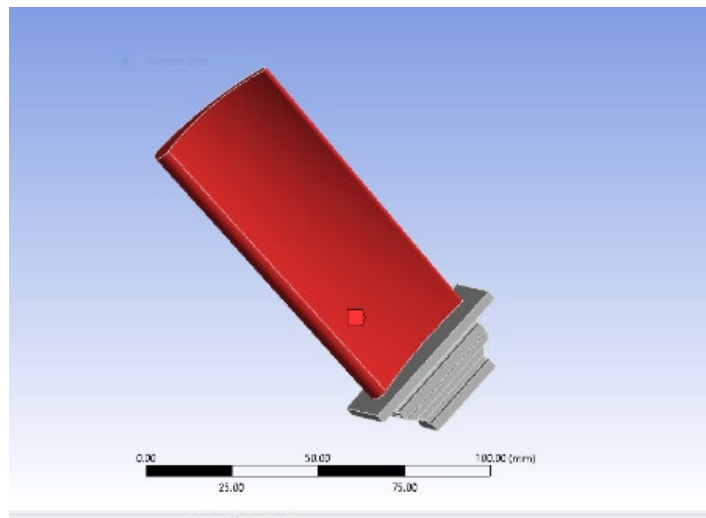


Fig.25 Boundary Conditions

E. Solution and Results

The thermal analysis was conducted to evaluate the temperature distribution, total heat flux, and directional heat flux within the gas turbine blade and the surrounding domain under the specified operating conditions. ANSYS software calculates temperatures and other required analyses at each node in the mesh until convergence is achieved. Once the analysis is performed, the result is analyzed and it consists of all required analyses. The results also enable us to see if the blade can withstand the thermal loads.

F. Temperature

Steady-state thermal analysis involves calculation and visualization of the distribution of temperature in a structure under constant heat source and thermal conditions, providing

important information to assess stability and safety regarding heat. The minimum temperature calculated by steady-state analysis is 250°C at the root, and the maximum has been found to be 500°C at the blade.

G. Total Heat Flux

Heat flux in steady-state heat transfer analysis refers to the heat energy passing through a surface or in a system, and it gives important information regarding heat transfer. The highest value of total heat flux obtained is 20.714 W/mm^2 , and the lowest is $6.1282\text{e-}16 \text{ W/mm}^2$. The highest total heat flux is at the interface of the root and turbine blade sections, as indicated below.

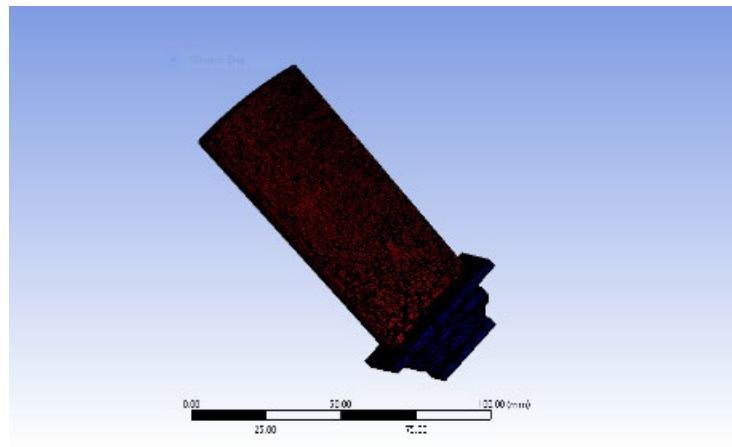


Fig.26 Temperature Analysis

H. Directional Heat Flux

The analysis of directional heat flux in steady-state thermal analysis is performed by analyzing heat flux, helping engineers maximize the cooling design of components such

as gas turbine blades. The maximum directional heat flux recorded was 12.853 W/mm^2 at the edge of the root section and blade, while the minimum was -11.907 W/mm^2 .

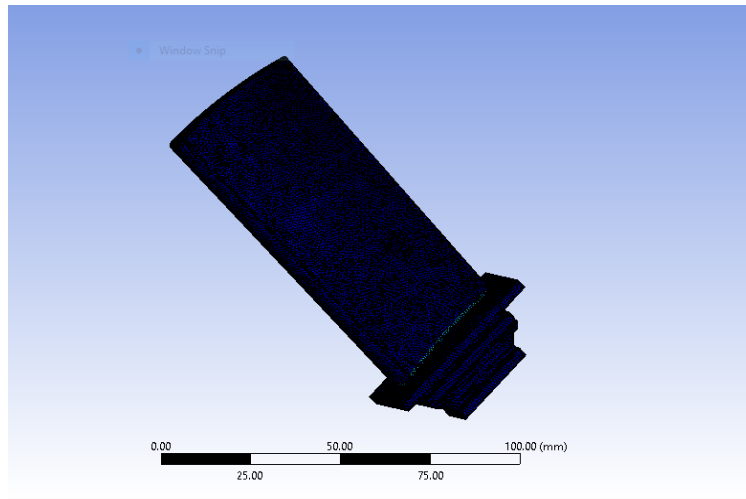


Fig.27 Total Heat Flux

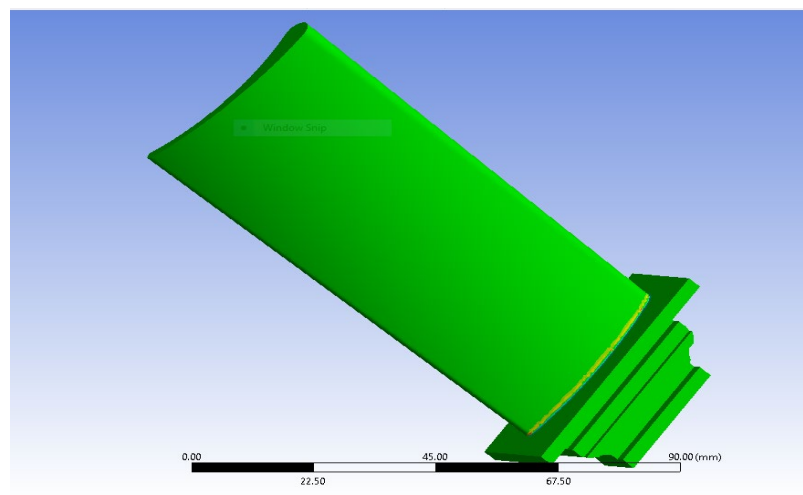


Fig.28 Directional Heat Flux

VII. STEADY-STATE THERMAL ANALYSIS ON COATED GAS TURBINE BLADE

Steady-state thermal analysis of a coated gas turbine blade using ANSYS is a numerical simulation approach that evaluates the blade's thermal behavior under continuous heat transfer conditions until thermal equilibrium is achieved. The coated gas turbine blade experiences temperatures due to the combustion of the fuel within the combustion chamber of the engine. It is important to analyze the coated gas turbine blade in order to determine how it operates under such conditions

to ensure its safety and functionality. The following is a description of steady-state thermal analysis of coated gas turbine blade using ANSYS:

A. Geometry

A three-dimensional model of the coated gas turbine blade and its associated components was previously developed in SolidWorks and subsequently imported into ANSYS, as illustrated in the figure below.

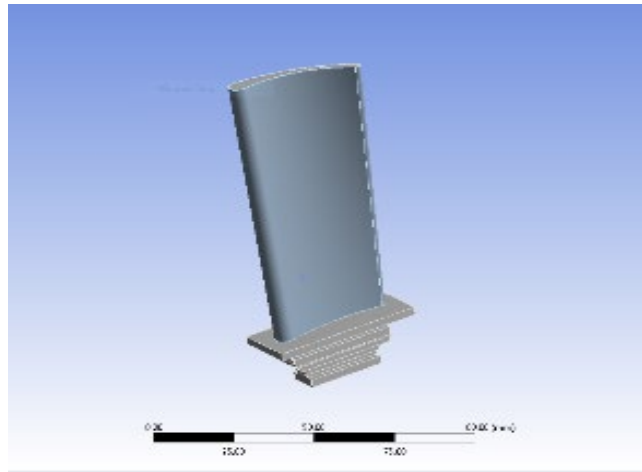


Fig.29 Geometry

B. Coordinate System

A schematic representation of the coordinate system established within the simulation environment is illustrated below.

C. Mesh Generation

A mesh for the coated gas turbine blade model was created. Thereafter, the model was divided into small elements; the

size of the elements was kept at 0.4 mm. Numerical analysis was carried out using ANSYS.

No changes were made to the mesh resolution, as its value was kept at the default. The fine and fast mesh option was chosen to create a high-quality mesh, as depicted in the following figure.

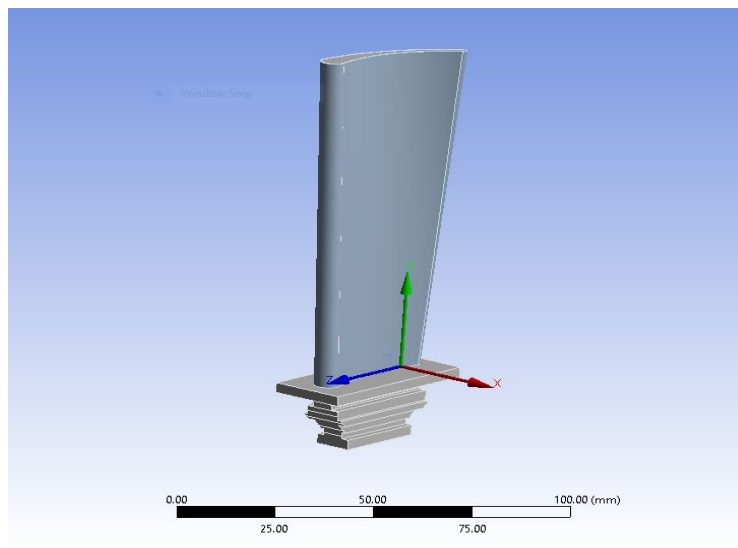


Fig.30 Coordinate System

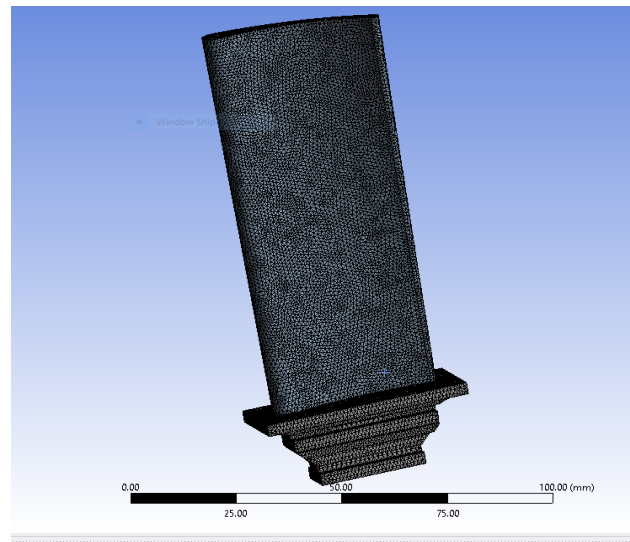


Fig.31 Mesh

D. Boundary Conditions

Boundary conditions were applied to both temperatures; one was the root temperature and the other was the blade

temperature. The root temperature was chosen to be 250°C, and 47 faces of the root were chosen. In contrast, the blade temperature was taken to be 500°C, and the blade faces were selected for it, as illustrated in the figure below.

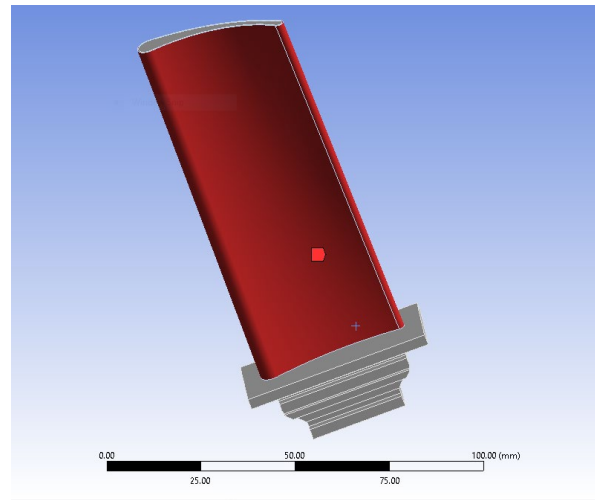
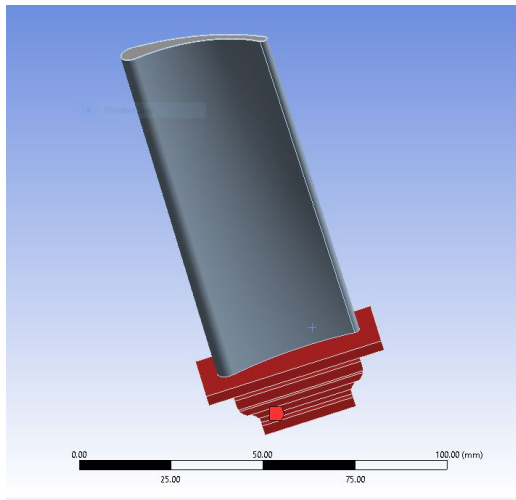


Fig.32 (a) Boundary Conditions (blade temperature); (b) Root Temperature

E. Solution and Results

The analysis was conducted to determine the temperature distribution, total heat flux, and directional heat flux within the gas turbine blade and its surrounding environment. ANSYS iteratively calculates the temperature and other required thermal parameters at each mesh node until the solution converges to a steady-state condition. After running the simulation, the result was analyzed and included all the required analyses. This result also helped to judge whether the blade would survive under such thermal loading or not.

F. Temperature

Steady-state thermal analysis allows one to determine and visualize the distribution of temperature within the structure with fixed sources and thermal conditions that help to assess thermal stability and safety. The minimum temperature value determined as a result of the analysis equals 78.702°C, while the maximum equals 455.9°C.

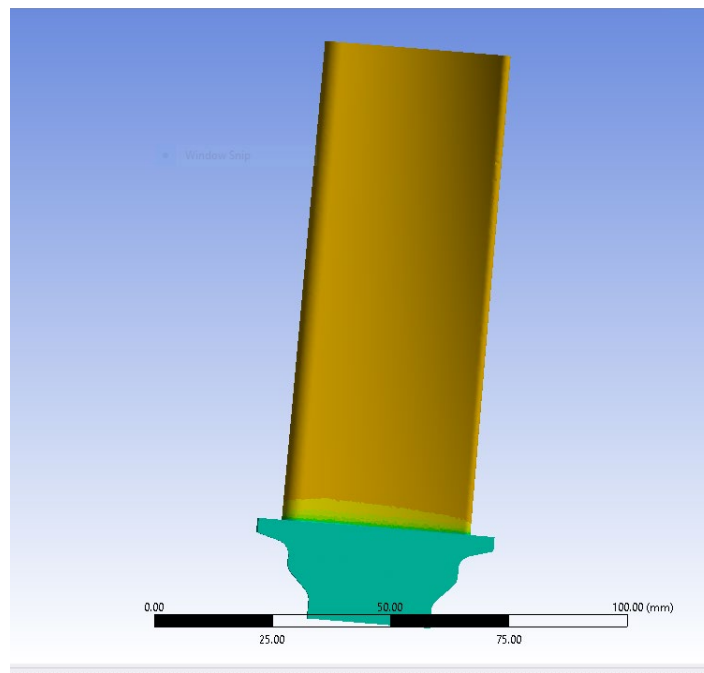


Fig.33 Temperature Analysis

G. Total Heat Flux

In steady-state thermal analysis, the total heat flux refers to the total amount of heat energy transmitted through the surface, which gives vital information on heat flow. The highest value of total heat flux obtained is 8.957 W/, while the lowest value is 1.1948e-15 W/.

H. Directional Heat Flux

The study of directional heat flux in steady-state thermal analysis examines the direction of heat transfer, which helps

engineers optimize cooling systems and improve the thermal efficiency of components such as gas turbine blades.

The highest value of directional heat flux is 4.070 W/mm², while the lowest is -2.9253 W/mm². Therefore, through steady-state thermal analysis in ANSYS, the behavior of the gas turbine blade can be understood.

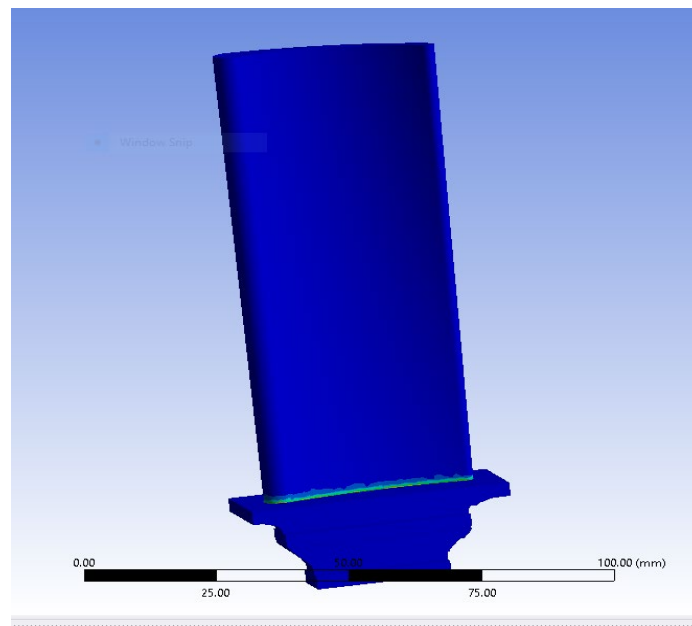


Fig.34 Total Heat Flux

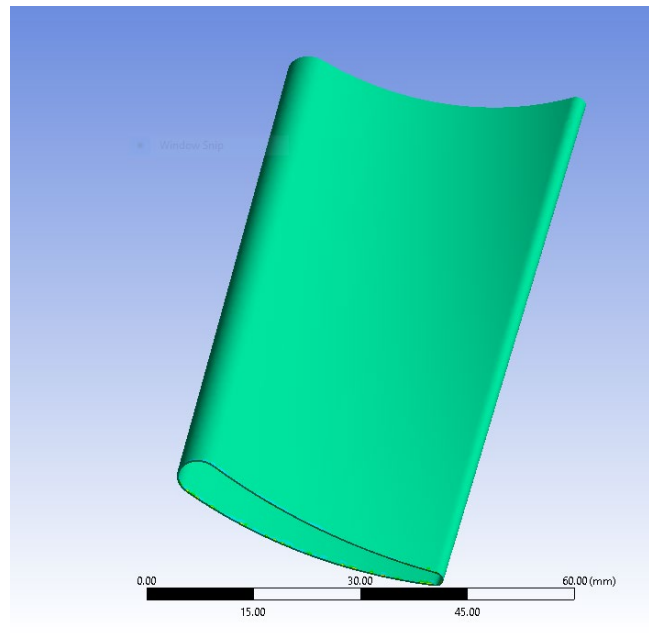


Fig.35 Directional Heat Flux

VIII. RESULTS AND DISCUSSION

In this research study, the primary objective was to design and evaluate metal–ceramic nanocomposite coatings using ANSYS for high-temperature applications, particularly for gas turbine blade protection. The coating system comprised a titanium alloy substrate with a YSZ coating layer. Static structural and steady-state thermal analyses were performed to investigate the mechanical and thermal performance of the coated blade.

A. Static Structural Analysis

The static structural analysis offered valuable information about the mechanical behavior of the uncoated and coated gas turbine blades. The maximum deformation of the uncoated blade is 0.5560 mm. The information obtained confirms that the blade is flexible and can deform due to external forces. This fact is consistent with expectations because titanium alloy is characterized by a high strength-to-weight ratio. The distribution of the equivalent stress varies from 0 MPa to 1336.6 MPa. The areas where the maximum stress is concentrated should be considered critical. It can be concluded that under extremely high operational loading conditions, the uncoated blade may be susceptible to stress-induced failure. The equivalent elastic strain values ranged from 2.843×10^{-15} to 0.0147, indicating the extent of deformation relative to the original geometry. The presence of elastic strain demonstrates the material's ability to undergo deformation while maintaining structural integrity without permanent damage. A certain level of strain is considered beneficial, as it reflects the material's capacity to withstand applied mechanical loads. After the incorporation of the YSZ coating, the results indicated a higher degree of deformation, with a maximum displacement of 0.6835 mm compared to the undeformed blade configuration. This implies that there has been an addition of a flexible layer to the material. In

addition, equivalent stress for the coated blade was found to vary between 0.039 MPa and 1122.1 MPa. In this case, there was an effective distribution of stresses over the surface of the blade by the coating. This shows that the coating can help in reducing stress concentrations and hence improve the structural integrity of the material. Equivalent elastic strain varied within a similar range as for the uncoated blade (0 to 0.0143). From this, it is clear that the use of the YSZ coating does not change the material deformation properties.

B. Steady-State Thermal Analysis

The steady-state thermal analysis was conducted to evaluate the temperature distribution and heat transfer characteristics of both uncoated and coated claddings. The directional heat flux for the uncoated cladding had a minimum of -11.907 W/m² and a maximum of 12.853 W/m². This wide variation shows the various thermal gradients encountered across the surface. The total heat flux had a minimum of 6.128e-16 W/m² and a maximum of 20.714 W/m², showing the heat flux that passed through the material. The temperature range of 250°C to 500°C represents the thermal gradient experienced by the uncoated cladding. After the application of the YSZ coating, the directional heat flux was reduced to values between -2.9253 W/m² and 4.0704 W/m². This means that there is controlled heat flux, which may reduce thermal stress within the material. The total heat flux range was between 1.1948e-15 W/m² and 8.957 W/m², meaning that there was better heat management. The temperature range was between 154.45°C and 447.19°C.

C. Discussion

The static structural analysis yielded useful results about the impact of the YSZ coating on the mechanical behavior of the gas turbine blade. It is particularly important that the maximum equivalent stress of the coated blade is less than

that of the uncoated one. It means that the coating manages to distribute the mechanical loads more evenly on the blade. In practice, it could result in increased strength of the material and decreased probability of its failure. In turn, it is an essential characteristic for the blade of the gas turbine. In addition, it is essential that the values of the equivalent elastic strain in both samples are equal. It shows that the YSZ coating does not prevent the material from deforming safely. Moreover, the increase in the deformation of the coated blade shows that the coating can make the blade more flexible, which will be helpful in case of regular temperature changes.

When analyzing the thermal behavior of the system in question, one should pay attention to the results of the steady-state thermal analysis. It is obvious that the reduced directional heat flux in the coated gas turbine blade demonstrates an improved heat distribution process. It means that there will be no hotspots that may cause the degradation of the material. Moreover, the decreased range of total heat flux values demonstrates that the coating is able to control the flow of heat effectively. As one can see from the results of the simulation, the YSZ coating significantly influences both the mechanical and thermal behavior of the gas turbine blade. It not only provides additional stress resistance due to the reduction of stress concentration points but also helps to achieve the controlled distribution of heat. Thus, these results correspond to the general information provided by the literature and modern industry requirements.

D. Conclusion and Future Recommendations

This research investigated the design and simulation-based assessment of Ytria-Stabilized Zirconia (YSZ) thermal barrier coatings applied to titanium alloy gas turbine blades for high-temperature applications. The study utilized SolidWorks for three-dimensional modelling and ANSYS for performing static structural and steady-state thermal analyses. Both coated and uncoated blade models were analyzed to assess the effect of the YSZ coating on the thermal and mechanical performance of gas turbine blades under operating conditions. The simulation results indicated that the application of the YSZ coating enhanced the overall thermal and structural performance of the blade. The static structural analysis revealed that the coated blade experienced lower equivalent stress compared to the uncoated blade, demonstrating improved stress distribution and greater structural stability. Although a minor increase in deformation was observed after coating application, the equivalent elastic strain values remained within acceptable limits, confirming that the coating maintained the mechanical integrity of the blade. Furthermore, the steady-state thermal analysis demonstrated significant improvements in thermal protection provided by the YSZ coating. The coated blade exhibited reduced temperature exposure, decreased total heat flux, and improved directional heat flux distribution compared with the uncoated blade. These findings highlight the effectiveness of YSZ as a thermal barrier coating for protecting titanium alloy substrates from severe thermal environments and reducing thermally induced stresses during gas turbine operation.

Overall, the research confirms that YSZ-coated titanium gas turbine blades offer enhanced thermal resistance, improved structural reliability, and better operational performance under high-temperature conditions. The findings of this study contribute to the advancement of thermal barrier coating technology for aerospace and power generation applications and demonstrate the importance of simulation-based approaches in the design and optimization of high-performance gas turbine components.

The following recommendations are proposed for future research to further improve the performance and practical applicability of thermal barrier coatings for gas turbine blades:

1. Experimental validation should be conducted to verify the simulation results under actual operating conditions and evaluate the real-world performance of YSZ-coated gas turbine blades.
2. Future studies should incorporate temperature-dependent material properties in ANSYS simulations to achieve more realistic and accurate analysis results at elevated temperatures.
3. Advanced computational models with complex blade geometries and realistic operating environments should be developed to better represent practical gas turbine systems.
4. Optimization studies should be carried out to determine the optimum coating thickness and composition for maximizing thermal protection, mechanical strength, and durability.
5. Additional coating materials and multilayer thermal barrier coating systems should be investigated and compared with YSZ to evaluate their effectiveness in high-temperature applications.
6. Long-term durability studies involving thermal cycling, oxidation resistance, corrosion behaviour, and fatigue analysis should be performed to assess coating reliability during extended service life.
7. Economic analysis should also be considered in future investigations to evaluate the cost-effectiveness of implementing thermal barrier coatings in industrial gas turbine systems.

In conclusion, this study provides a strong foundation for the simulation, analysis, and development of advanced thermal barrier coating systems for gas turbine blades operating under high-temperature conditions. Further experimental and computational investigations can contribute significantly to improving turbine efficiency, operational reliability, and component lifespan in aerospace and power generation industries.

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Declaration of Conflicting Interests

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Use of Artificial Intelligence (AI)-Assisted Technology for Manuscript Preparation

The authors confirm that no AI-assisted technologies were used in the preparation or writing of the manuscript, and no images were altered using AI.

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