RESEARCH ARTICLE

Investigation of Gas Turbine Blade Materials for Efficient Energy System

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Received: 28 October, 2023, Accepted: 24 November, 2023, Published: 29 November, 2023

Abstract

The present study aims to determine the best and most economical material for a gas turbine blade, which operates under high-temperature conditions and experiences high static structural and thermal loads. To achieve this objective, three different types of material alloys, namely Titanium alloy Ti6AL4V, Magnesium alloy AZ80, and Aluminum alloy 7075-T6, were selected for comparison. A turbine blade model was designed using Solid Works software, and structural and thermal analyses were performed using ANYAS 15.0 under steady-state conditions. The structural analysis aimed to determine the stress, strain, and deformation results on turbine blades by applying high pressure, while the thermal analysis aimed to determine the temperature distribution influences and heat flux generation by applying high temperatures. Based on the results obtained from both analyses of the three different materials, Titanium alloy Ti6AL4V is the best and most economical material. This material showed low stress, strain, and little deformation and the best material properties at high temperatures when compared to Magnesium alloy AZ80 and Aluminum alloy 7075-T6.

Keywords: Energy Generation; Gas Turbine; Structural analysis; Thermal analysis

Introduction

Gas turbines are a type of engine that is highly efficient and versatile, making them a popular choice in a variety of industries (Gallardo, Rodríguez et al. 2002, Swain, Mallick et al. 2020). They are commonly used in power plants to generate electricity, where they burn natural gas, diesel, or other fuels to produce high-pressure gas that is used to drive the turbine and generate power (Sivakumar and Mordike 1989, Salwan, Subbarao et al. 2021). Additionally, gas turbines, also known as jet engines, are used to propel airplanes by taking in air, compressing it, mixing it with fuel, igniting the mixture, and then expelling the combustion products to create thrust (Chowdhury, Mohsin et al. 2023, Courtis, Skamniotis et al. 2023). Their high power-to-weight ratio enables quick acceleration and maneuverability, making them a popular choice for naval ships and high-speed vessels (Liu, Han et al. 2023, Nourin and Amano 2023).

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Furthermore, gas turbines are used in mechanical drive applications in various industries, such as driving compressors, pumps, and generators (Soori, Asmael et al. 2023). They provide reliable and efficient power and are commonly used in the oil and gas sector for powering drilling equipment, gas compression, and as prime movers for natural gas pipeline compressors (Sharif, Noon et al. , Sharif, Tipu et al. , Ullah, Siddiqi et al. , Ullah and Sharif 2022).
A gas turbine is an internal combustion engine that generates power by turning a turbine with hot, fuel- and gas-burning air (Ujade and Bhambere 2014, Sharif, Siddiqi et al. 2020, Habib, Sharif et al. 2021). Basically, a gas turbine works identically as a steam turbine, except that it uses air instead of water. Fresh air is initially compressed and subjected to a high pressure, after which energy is supplied by fuels injected into the combustion chamber, resulting in a high temperature. As a result of the high pressure and temperature hitting the turbine, the shaft work output operates the electric generator (Jabbar, Rai et al. 2014, Htwe, Win et al. 2015). A gas turbine engine is a machine that generates mechanical power by using a gaseous working fluid. The steady flow of the operating fluid of a gas turbine is its primary advantage over reciprocating Otto and diesel engines. The Brayton cycle constitutes the foundation for gas turbine engine thermodynamics (Kumar and Pandey 2017, Habib, Sharif et al. 2022). Many applications use a gas turbine; an electro-mechanical device that continuously produces power (Sharif, Siddiqi et al. , Muhammad, Sharif et al. 2022). The primary indications of turbine blade failure, which depend on the aforementioned variables, are high stresses, high vibrations, and high thermal effects (Chintala and Gudimetla 2014). A material that is appropriate for use in gas turbine blades has to possess three mechanical properties: young modulus, shear strength, and fatigue resistance. The material must be suitably ductile and durable (Noon[1], Arif[1] et al. 2021, Shoukat, Noon et al. 2021). The gas turbine uses the energy of the air and gases that have been burned to produce electricity by expanding through the numerous rings of static and moving blades.

Literature Review

Extensive research in the field of aerospace engineering and materials science has been dedicated to the investigation of gas turbine blade materials. The optimization of gas turbine blade performance and durability has been the primary focus of numerous studies due to its crucial role as a component in aircraft engines and power generation systems. In the past, few researchers work on the gas turbine blade and its materials. According to evidence, up to 50% of the blades in some machines had cracks in the hollow center of the leading edge tips, and the failure was caused by a fissure that spread over the whole wall thickness of the blade (Tari 2000). The cooling of the turbines after they acquire a highest working temperature is one of the major difficulties in gas turbine design (HAN and Dutta 2001). High cycle fatigue of the compressor and turbine blades, which has become a typical failure mode for turbo machinery, is caused by high fluctuation loads imposed on the machinery by blade vibration resonance within the machinery's operating range (Chamis and Abumeri 2003). In order to boost the design capabilities for high-temperature turbines, researchers have carried out an experimental study program to provide a full, comprehensive knowledge and data base of turbine flow fields and their influence on heat transfer (Hacker 2000). It was investigated the consequences of rapid velocity on the composite blade. Results reveal that the blade has a significant damage tolerance at 0.01 chances of structural failure and comparatively low degradation intolerance at 0.999 probabilities (Lim and Menq 1994). Worked performed on the design and thermal analysis of gas turbine rotor blade on which cosmos software is used for the analysis of finite element method of gas turbine blade and design calculation is induced by MATLAB software by selecting three different materials titanium, nickel and copper. Total thermal heat flux of theoretical result for titanium alloy is 0.9927MW/m^2 ,copper is 2.6453 MW/m^2 and for nickle is 1.95559

MW/m^2 also simulation results of total thermal heat flux for titanium alloy is 1.1503 MW/m^2 ,copper is 3.0060 MW/m^2 and for nickle material is 2.1810 $MW/m^2$and for nickle material is 2.1810 MW/m^2.According to the results comparsion of theortical and simulation results titanium alloy material has the least heat flux as compared to copper and nickle alloy,So the titanium alloy is better than the other two alloy materials (Htwe, Win et al. 2015). Operating temperature of the turbine's inlet establishes the turbine's efficiency, but it also signals that material limitations and stressful conditions will prevent the turbine blades from withstanding such high temperatures (Jabbar, Rai et al. 2014). The surface coating of gas turbine blades against oxidation, corrosion, and erosion is paramount for their improved performance and longevity. To achieve this, several research investigations have been undertaken to develop cutting-edge coating technologies, such as thermal barrier coatings (TBCs) and environmental barrier coatings (EBCs). These advanced coatings aim to enhance the efficacy and resilience of the blades (Fathyunes and Mohtadi-Bonab 2023).

A lot of works were performed on gas turbine blade materials, but still there is lack of efficient material to enhance the efficiency of the gas power plant. In this study, various materials are considered and compared the structural and thermal analysis to investigate the more efficient and economical material that will increase the overall performance of the gas turbine. The objective of this project is to design a gas turbine blade and then develop the structural and thermal analysis on it to investigate and suggest the best and economical material.

Material and Methods

Materials

Titanium alloy TiAL4V

Titanium alloy Ti6AL4V is widely recognized for its exceptional strength-to-weight ratio, corrosion resistance, and biocompatibility, making it a popular material for various industries. The aerospace sector is the material of choice for aircraft components such as structural elements, engine parts, and landing gear components due to its lightweight and robust mechanical properties. In the medical field, Ti6AL4V is commonly employed for implants and prosthetics owing to its biocompatibility and resistance to bodily fluids. Furthermore, this alloy is used for lightweight and durable components in the automotive industry, resulting in improved fuel efficiency (Boshoman, Fatoba et al. 2023). Its corrosion resistance makes it suitable for marine structures and components in the marine sector. Additionally, Ti6AL4V finds use in chemical processing, power generation, and sports equipment, demonstrating its versatility in addressing demanding requirements across various industrial applications.

Magnesium alloy AZ80

Magnesium alloy AZ80 possesses a remarkable strength-to-weight ratio and is well-known for its lightweight nature, making it an attractive option for various industrial applications. Its low density and remarkable mechanical properties make it popular for manufacturing lightweight components in the automotive industry, contributing to reduced fuel consumption and lower emissions. Furthermore, AZ80's impressive corrosion resistance renders it an ideal option for aerospace applications, where it is utilized in producing aircraft structures and components. Additionally, the alloy's biocompatibility and ability to dissolve in the body make it suitable for medical implants and orthopedic devices (Naik, Sharma et al. 2023). The electronics industry also benefits from AZ80's properties, utilizing it for casings and components owing to its low density and good mechanical properties. Finally, AZ80's exceptional thermal conductivity and heat dissipation properties enable it to be used in select applications in the electronics and telecommunications industries. In conclusion, the unique combination of mechanical strength and lightweight design makes magnesium alloy AZ80 highly desirable in various industrial sectors (Zhang, Yuan et al. 2023).

Aluminum alloy 7075-T6

Aluminum alloy 7075-T6, a material highly regarded for its exceptional mechanical properties and high strength-to-weight ratio, has found extensive usage in diverse industries. In the aerospace sector, the alloy is considered a vital component for aircraft structures, including fuselage components, wing structures, and critical structural elements, owing to its lightweight and exceptional strength (Habib, Sharif et al. 2021). Similarly, the automotive industry has also widely employed this alloy for producing high-performance vehicle components, such as suspension components, chassis parts, and wheels, which have enhanced fuel efficiency and overall performance. In addition, the alloy's durability and resilience make it a preferred choice for manufacturing precision equipment, including firearm components. Furthermore, the sporting goods industry has also taken advantage of its strength and lightweight characteristics by utilizing it for bicycle frames and other athletic equipment. The alloy's corrosion resistance further makes it useful in marine and naval constructions. In conclusion, the versatility of aluminum alloy 7075-T6 makes it a crucial material in various industrial applications, where the combination of strength, low density, and corrosion resistance is vital (Habib, Sharif et al. 2021).

Design and Cad Modelling of Blade

The gas turbine blade is designed in solid work software and then imported into ANSYS software 15.0 (Sharif, Siddiqi et al. , Tipu, Arif et al.). The design was based on previous study that enhances to increase the efficiency of the turbine blade. The 3D CAD model is shown in Figure 1 and design parameters are as shown in Table 1. Moreover, properties of gas turbine blade materials are as shown in Table 2.

Table-1: Design Parameters of Gas turbine Blade

Parameter	value	unit
Blade height, h	0.8	m
Chord width, c	0.322	m
Pitch,s	0.224	m
Blade inlet angle, β2	16.2	degree
Blade outlet angle, β3	52.7	degree

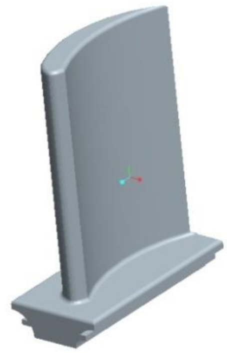


Figure 1: Turbine Blade Geometry

Table 2: Properties of materials alloys used in analysis (Hussain, Sharif et al. , Habib, Sharif et al. 2022, Sharif 2022, Aamir, Sharif et al. 2023, Sharif, Hussain et al. 2023, Sharif, Khan et al. 2023)

Material	Aluminum 7075-T6	Magnesium AZ80	Titanium Ti6AL4V
Yield Strength (Mpa)	510	380	880
Melting Temperature (℃)	640	672	1660
Density (Kg/mm³)	0.281	0.18	0.8
Thermal Conductivity (W/m-K)	130	24	6.7
Specific Heat (J/Kg-K)	870	990	520

Finite Element Analysis of Blade

In current work FEA software (ANSYS 15.0) is used for thermal and structural analysis of gas turbine blade, to investigate and suggest the best material for turbine blade to be newly manufactures. Structural and Thermal analysis is performed by ANSYS 15.0 software. The analysis is carried out under steady state condition i.e., Steady state static structural and Steady state Thermal stresses.

Structural Analysis

After generating 3D model in Solid work software, the geometry is then importing into ANSYS 15.0 software to generate mesh as shown in figure 2. A fixed support to the model from bottom and then apply 10^6 pa or 1 Mpa pressure to the front of blade. In data we take 1mpa pressure=10^6 pa so we convert all data to Mpa in experimental results.

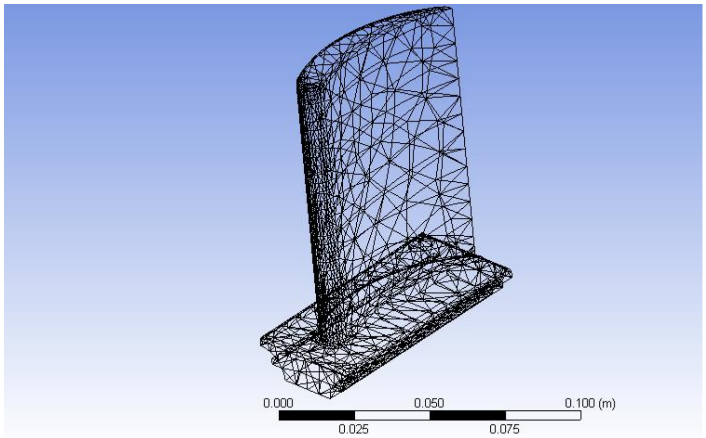


Figure 2: Mesh generation

Titanium Alloy (TiAl4V)

Maximum stress, Maximum Strain and Total Deformation

Maximum stress is seen in root of blade and minimum stress is at on top of blade tip as shown in figure 3. Maximum strain is seen in root of blade and minimum strain is at on top of blade tip as shown in figure 4. Maximum deformation is at top of blade tip and minimum deformation is at root of blade as shown in figure 5.

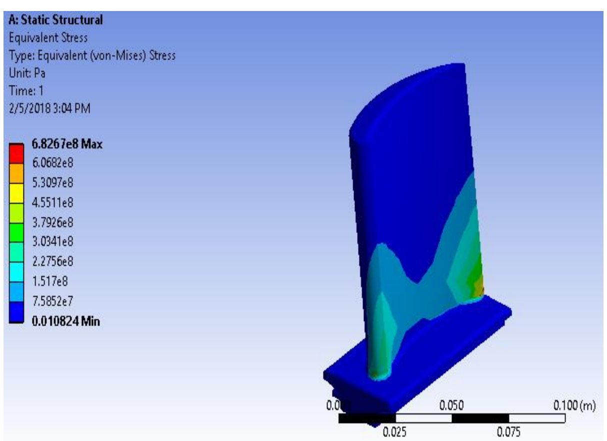


Figure 3: Equivalent Stress Distribution

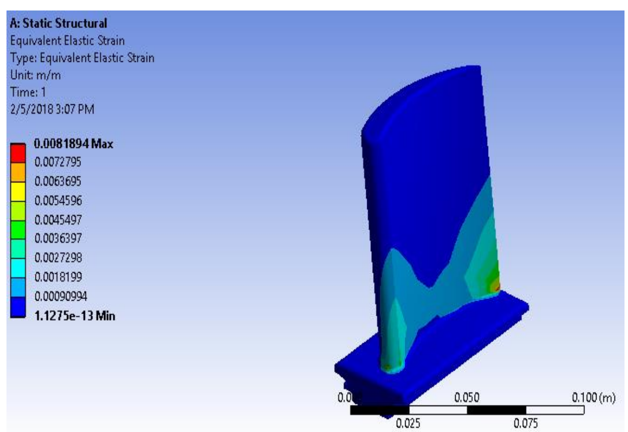


Figure 4: Equivalent Strain Distribution

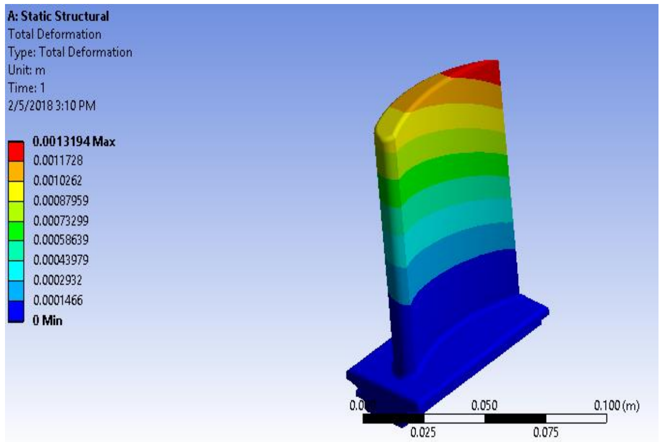
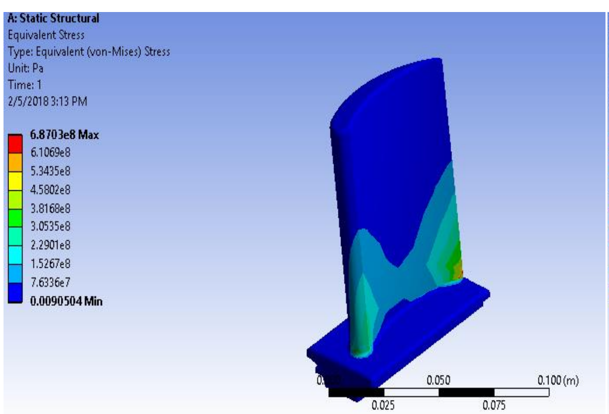


Figure 5: Equivalent Total Deformations

Magnesium Alloy (AZ80)

Maximum stress, Maximum strain and Total Deformation

Maximum stress is seen in root of blade and minimum stress is at on top of blade tip as shown in figure 6. Maximum strain is seen in root of blade and minimum strain is on top of blade tip as shown in figure 7. Maximum deformation is at top of blade tip and minimum deformation is at root of blade as shown in figure 8.



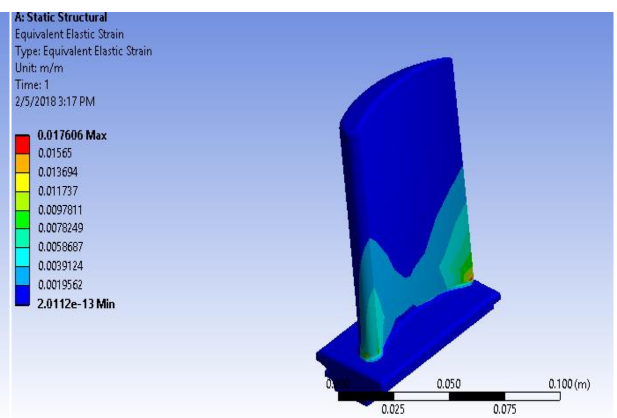


Figure 6: Equivalent Stress distribution

Figure 7: Equivalent Strain distributions

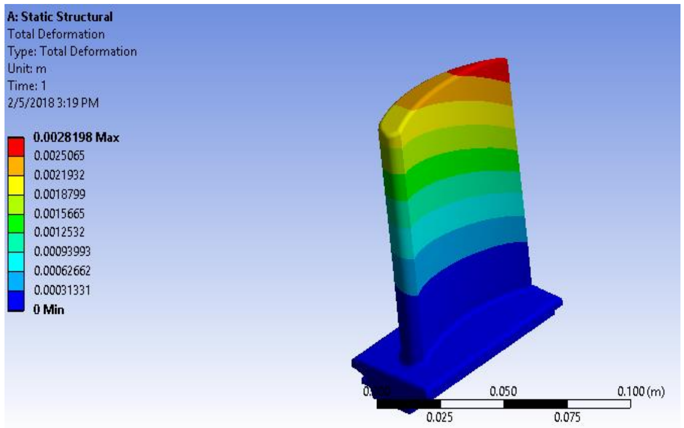
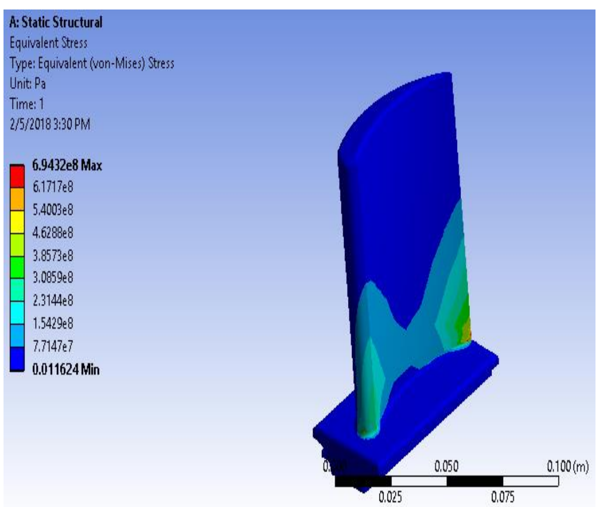


Figure 8: Equivalent Total Deformations

Aluminum Alloy (7075-T6)

Maximum stress is seen in root of blade and minimum stress is on top of blade tip as shown in figure 9. Maximum strain is seen in root of blade and minimum strain is on top of blade tip as shown in figure 10. Maximum deformation is at top of blade tip and minimum deformation is at root of blade as shown in figure 11.



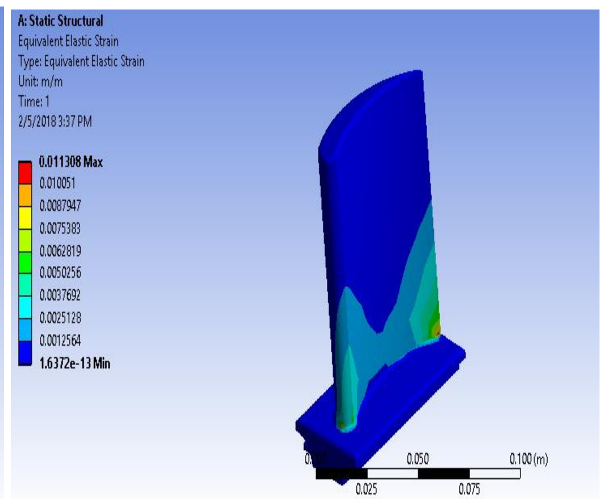


Figure 9: Equivalent Stress distribution   Figure 10: Equivalent Stress distributions

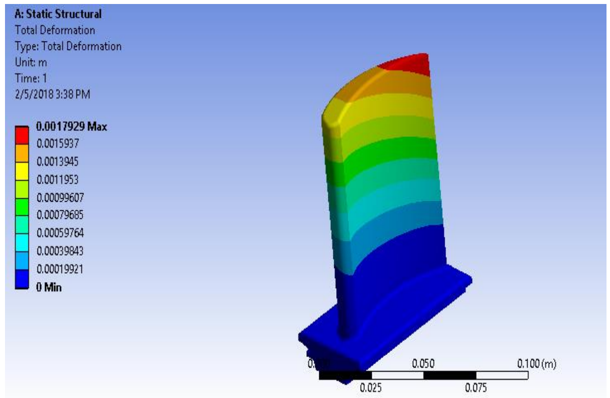


Figure 11: Equivalent Total Deformations

From above results Titanium Alloy have low stress, strain and low deformation as compared to other two material alloys on applying same 10^6 pa or 1 Mpa pressure.

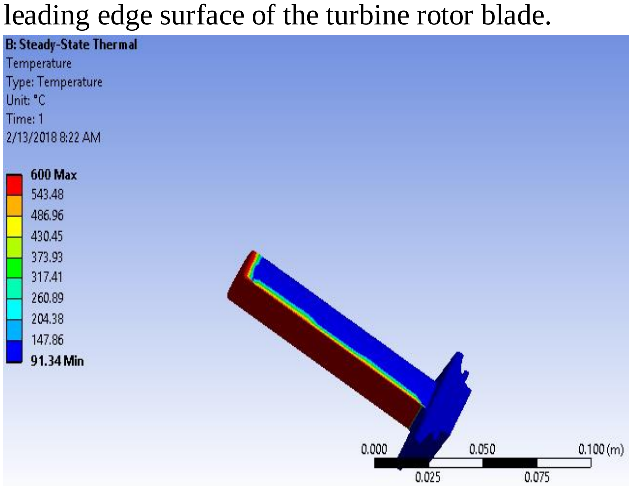
Thermal Analysis of Gas Turbine Blade

In Steady state thermal analysis, we find temperature distribution and total thermal heat fluxes on different materials alloy.

Maximum Temperature, Total Thermal Heat Flux

Titanium Alloy (TiAl4V)

As per the observations, the maximum temperature is found at the trailing edge surface of the rotor blade while the minimum temperature is found at the leading edge surface and bottom flat. Additionally, figure 12 shows the graphical representation of the same. On the other hand, figure 13 represents that the maximum total thermal heat flux is observed at the trailing edge surface and the minimum total thermal heat flux can be seen at the leading edge surface of the turbine rotor blade.



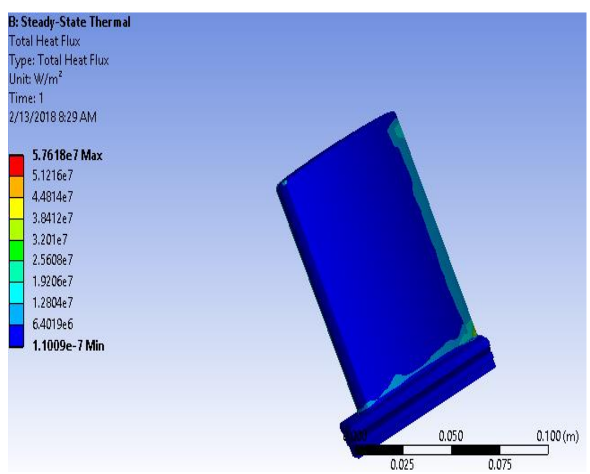
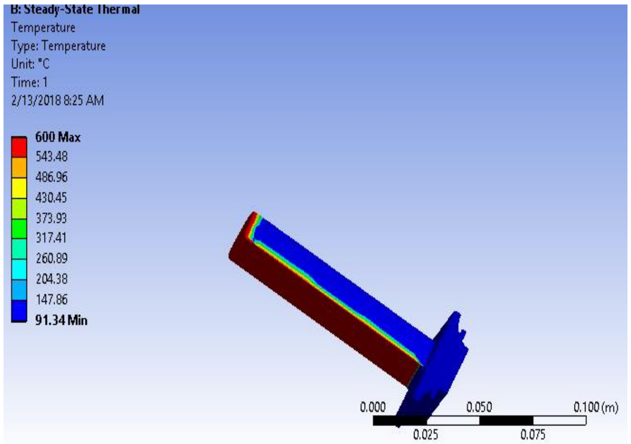


Figure 12: Total Temperature distribution

Figure 13: Total Heat Flux

Magnesium Alloy (AZ80)

The temperature distribution on the rotor blade is quite interesting. The highest temperature can be found on the trailing edge surface, whereas the lowest temperature is observed on the leading edge surface and the bottom flat of the rotor blade. This is clearly depicted in figure 14. Additionally, the maximum total thermal heat flux is noticed on the trailing edge surface, while the minimum total thermal heat flux is observed on the leading edge surface of the turbine rotor blade as shown in figure 15.



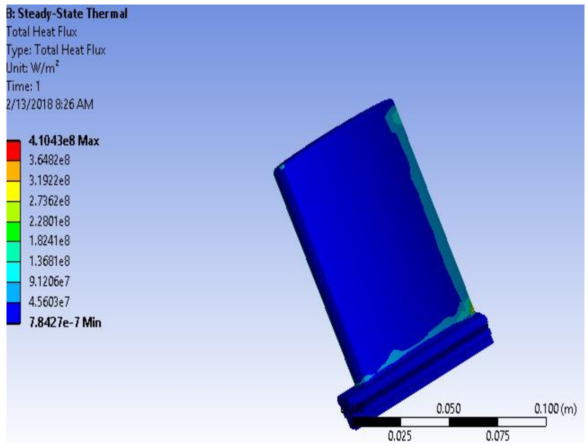
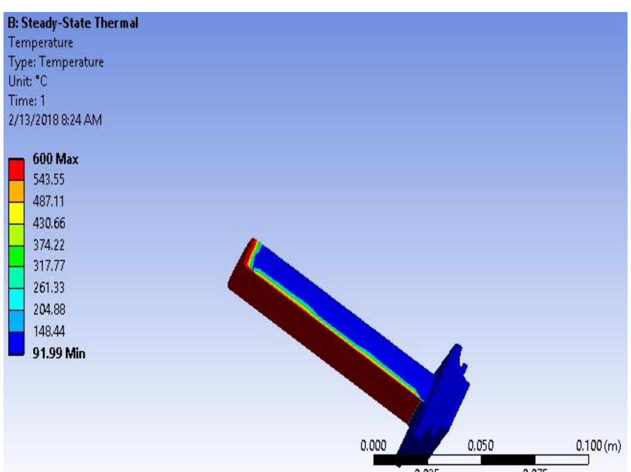


Figure 14: Total Temperature distribution

Figure 15: Total Heat Flux

Aluminum Alloy (7075-T6)

According to figure 16, the highest temperature is observed on the trailing edge surface of the rotor blade, while the lowest temperature is observed on the leading edge surface and bottom flat of the blade. Similarly, figure 17 shows that the maximum total thermal heat flux is observed on the trailing edge surface, while the minimum total thermal heat flux is seen on the leading edge surface of the turbine rotor blade.



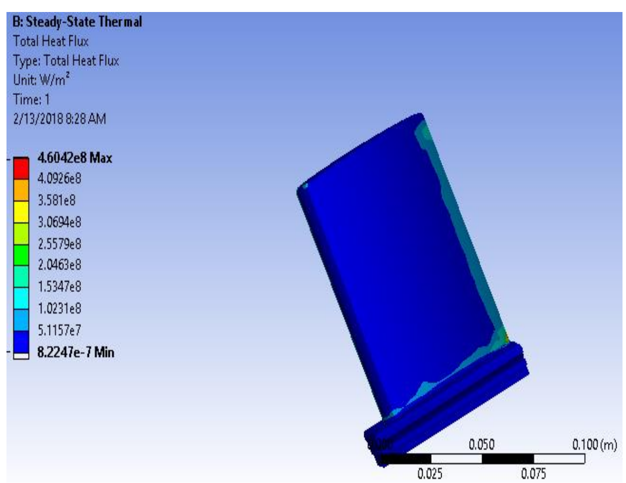


Figure 16: Total Temperature distribution

Figure 17: Total Heat Flux

The Experimental Results of Structural and Thermal Analysis of Gas Turbine Blade are as shown in table 3 and 4.

Table 3: Structural Analysis of Gas Turbine Blade

Materials	Stress (Mpa) (max)	Strain (m/m) (max)	Total Deformation (m) (max)
Titanium Alloy (TiAl4V)	682.67	0.00818994	0.0013194
Magnesium Alloy (AZ80)	687.03	0.017606	0.0028198
Aluminum Alloy (7075-T6)	694.32	0.011308	0.0017929

Table 4: Thermal Analysis of Gas Turbine Blade

Materials	Temp- Distribution (Max)	Temp- Distribution (Min	Total Heat Flux (w/m²)
Titanium Alloy (TiAl4V)	600	91.34	$5.7618e^7$
Magnesium Alloy (AZ80)	600	91.35	$4.1043e^8$
Aluminum Alloy (7075-T6)	600	91.99	$4.6042e^8$

Conclusion

This study was conducted to investigate the optimal materials that can be used to enhance the efficiency of gas turbine blades. The study involved the application of a pressure of 10^6 Pa to blades made of three different materials, namely, magnesium alloy, titanium alloy, and aluminum alloy. The study findings provide significant insights into these materials' structural and thermal performance.

The static structural analysis evaluated maximum stress, strain, and deformations when a pressure of 10^6 Pa was applied. The results showed that titanium alloy outperformed magnesium and aluminum alloy. It demonstrated the least stress and strain values and the least deformation, indicating its superior structural integrity and resistance to applied pressure. This underscores titanium alloy's capability to withstand operational loads more effectively than its counterparts.

Moreover, in the steady-state thermal analysis, the study evaluated each material's total temperature and thermal heat flux at a maximum temperature of 600 C°. The results showed that titanium alloy consistently outperformed magnesium and aluminum alloy regarding total temperature and thermal heat flux. This suggests that titanium alloy exhibits superior thermal stability and heat dissipation characteristics, crucial factors in the demanding conditions of gas turbine operation.

Overall, analyzing static structural and thermal behavior establishes titanium alloy as the optimal material for gas turbine blades. Its exceptional performance in stress resistance, strain tolerance, deformation characteristics, and thermal stability makes titanium alloy the most suitable choice for enhancing the efficiency and durability of gas turbines. This study provides valuable insights into gas turbine materials engineering, contributing to informed decision-making in designing and manufacturing high-performance turbine blades.

Declaration

Acknowledgment: The authors are highly grateful to CECOS University and University of Engineering and Technology, Lahore, Pakistan for the support and facilitation

Funding: This research received no external funding

Conflict of interest: There is no conflict of interest

Author's contribution: Conceptualization, I.U., N.B.; methodology, N.B.; Simulation, I.U,; investigation, N.B.; writing—original draft preparation, I.U,; writing—review and editing, N.B

Data availability: The data presented in this study are available on request

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