THERMAL CONDUCTIVITY ANALYSIS OF NICKEL AND COBALT AS MATERIALS FOR TURBINE BLADE MANUFACTURING

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ABSTRACT

Turbine blades experience degradation when exposed to high temperatures because they operate in extremely harsh environments where thermal, mechanical, and chemical stresses occur simultaneously. The selection of turbine blade material is crucial for ensuring the reliability, efficiency, and performance of aircraft engines. Advanced materials are employed to withstand high temperatures, pressures, and dynamic stresses, ultimately contributing to the overall effectiveness and safety of aircraft engines. The aim of this study is to conduct a comparative thermal analysis to ascertain the thermal capacity of nickel and cobalt. An attempt was made to use cobalt and nickel as turbine blade materials and steady state thermal analysis was carried out on ANSYS under temperature condition of 500C, 1000C and1500C. From the thermal analysis, cobalt maintained structural integrity at a temperature of 1495C. On the other hand, nickel material showed signs of degradation below 1495C. This shows that cobalt is a more suitable option to be used for turbine blade material. This is because of its high thermal strength and thermal conductivity. It is recommended to explore research on developing an alloy of cobalt to withstand a temperature beyond 2000C.

Keywords: Turbine blade, Materials, Reliability, Dynamic stress, Temperature, thermal conductivity.

1 INTRODUCTION

Gas turbine engines are widely used in various aircraft, including passenger jets, military fighter aircraft, and helicopters [1]. They are the most important propulsion system for aviation, providing the necessary thrust to move the aircraft through the air [2]. The turbine section is a vital component of the gas turbine engine, as it converts the thermal energy from the combustion process into mechanical energy that powers the engine and the aircraft[3]. The gas turbine engine compromises of three main parts, airlet, compressors and the turbine section [4]. Turbine blades are radial aerofoils mounted in the rim of a turbine disc that extract energy from high-temperature, high-pressure gas produced by the combustor in gas turbine engines [1, 5]. The turbine section of the gas turbine engine is exposed to the harshest environment in terms of temperature and pressure, so turbine blades need to be made of heat-resistant alloys such as Co- and Ni-based superalloys [2, 6]. Modern turbine blades often use nickel-based superalloys that incorporate chromium, cobalt, and rhenium, which help resist creep [7, 8]. Turbine blades are carefully designed to optimize their aerodynamic performance and energy extraction, and they experience mechanical stresses in the severe working environment [9, 10]. Turbine blade temperatures can exceed 1200°C and reach up to 1500°C in the latest engines [7, 11]. Cooling passages, thermal barrier coatings, and high-temperature corrosion-resistant alloys like Ni-Co-Cr-Al-Y can be used to improve turbine blade performance [6]. Turbine blade material is crucial to the performance and durability of gas turbine engines in aircraft and superalloys are commonly used due to their high temperature strength and corrosion resistance [7]. The components of a turbine blade include the root which connects the blade to the turbine disc and provides structural support [1]. Shroud: The shroud stabilizes the blades and prevents leakage. Airfoil: The airfoil is the part that interacts with the gas or steam or fluid passing by, converting the energy of the bypassing gas into mechanical work. Figure 1 and 2 show turbine blades which are the principal elements that convert the pressure energy of working fluid into kinetic energy. Turbine blades are of two basic types: moving blades and fixed blades [2]. Turbine blades can be classified based on their geometry and energy conversion process as impulse or reaction turbine blades. The most common types of turbine blades used in gas turbine engines are axial turbine blades and compressor blades, which consist of multiple stages and are designed to ensure the energy transfer between the gas and the rotor. Turbine blades are often made of exotic materials like superalloys and use different cooling methods, such as internal air channels, boundary layer cooling, and thermal barrier coatings, to withstand the harsh environment [1].

Figure 1. Rotor blade [12]

Figure 2. Single turbine blade [12]

Research has been conducted to evaluate the use of various materials like glass fiber-reinforced plastic, carbon fiber-reinforced plastic, different aluminum alloys, and bamboo-based composites for turbine blades [13]. Over the years, there have been significant advancements in the materials and production methods used for turbine blades. Turbine blades often use exotic materials like superalloys and employ various cooling methods, including internal and external cooling, as well as thermal barrier coatings to withstand the harsh operating condition [14]. Most turbine blades are manufactured by investment casting, involving the creation of a precise negative die of the blade shape filled with wax to form the blade, and the use of ceramic cores for hollow blades [15]. One significant advancement in turbine blade technology is the development of single crystal turbine blades. These blades are made from a single crystal, which provides superior strength and resistance to high temperatures. The development of single crystal turbine blades has been a game-changing technology breakthrough, significantly improving the performance and durability of gas turbine engines [14]. Engineers have also made advancements in the structure of turbine blades, particularly in the 1960s, by rethinking the material structure of the blades [15]. Conventionally cast turbine airfoils are polycrystalline, consisting of a three-dimensional mosaic of small metallic crystals, or grains, formed during solidification in the casting mold [16]. However, the development of directionally solidified turbine blades has significantly improved ductility, thermal fatigue life, and tolerance to localized strains, contributing to increased turbine temperature and efficiency [17]. In conclusion, the history of turbine blades is marked by continuous advancements in materials, production methods, and blade structure, leading to improved performance, durability, and efficiency of gas turbine engines and steam turbines.

2 METHODOLOGY

This section describes the precise methodology employed in this project. CATIA was used to design the turbine blade model, and ANSYS was used to perform steady state thermal analysis for various temperature condition of 500C,1000C, 1500C with nickel, cobalt, inconel 718 and titanium alloy.

2.1 Software tools

The software tools include: Microsoft Excel, CATIA, and ANSYS. Microsoft Excel is a powerful spreadsheet editor developed by Microsoft for various platforms [18]. It offers calculation capabilities, graphing tools, pivot tables, and a macro programming language called Visual Basic for Applications (VBA) [18]. For the turbine design. This software was used to plot aerofoil coordinates and turbine blade parameters into CATIA. CATIA is a multi-platform software suite developed by the French company Dassault Systèmes [19]. It is used for computer-aided design, computer-aided manufacturing, computer-aided engineering, 3D modeling, and product lifecycle management [20]. This software was used for the design of the turbine blade. ANSYS is a software suite that provides simulation solutions for computer-aided engineering, product design, and product development [10, 21]. The software was used for the simulation of the thermal analysis on the proposed materials. The CAD modelling of the turbine is presented below:

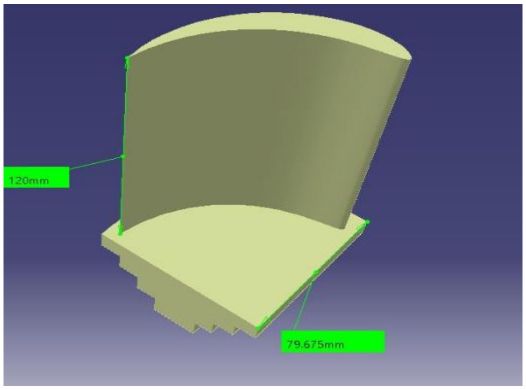


Figure 3. Turbine blade design model

Table 1. Turbine blade dimension

S/N	Part	Size (mm)
1	Chord	100
2	Radius(mm)	70
3	Thickness	3
4	Blade axial chord length	79.675
5	Blade span	120

Step by step procedure analysis in ANSYS

The ansys software was launched →clicked on steady state thermal on the work bench; click on engineering data →engineering data base→select the proposed materials. click geometry →import the IGS file from catia→generate then exit the workbench; Then on mode → assign the part body→ assign the proposed material to the model; click on mesh→click on sizing which is 1mm →behavior to be hard. then the temperature, convection and heat flow will be inserted; clicked on solution → click on solve.

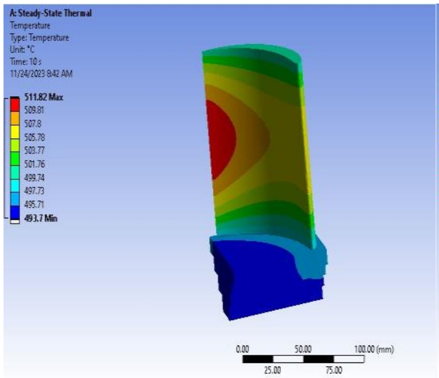
3 RESULTS AND DISCUSSION

3.1 Steady state thermal analysis results

The thermal analysis of the turbine blade is considered for two proposed material namely, nickel and cobalt to determine their relative capability to withstand high temperature that is up 1500 which are generally encountered in the turbine section. This work involves the study of various temperatures with different materials using steady state thermal analysis. Steady state analysis refers to a situation in which the variables describing the behavior of a material or process remain constant over time. The thermal analysis was performed on various temperatures of 500, 1000 and 1500 with the proposed materials. The thermal resistance of any material greatly depend on its thermal Conductivity, among the two proposed materials, cobalt has the highest thermal conductivity of 100W/(m K) at room temperature. In terms of thermal strength, Cobalt has a maximum temperature of 1495°C, nickel has a maximum temperature of 1455°C. It was observed through steady state thermal analysis that all the materials maintained their temperature distribution without deformation at 500°C, at 1000°C only TI-6AI-4V and nickel temperature distribution change and will start deformation in due time, at 1500°C only cobalt temperature distribution did not change but the temperature distribution of Nickel changed as a result of its low thermal conductivity. From the thermal analysis performed, cobalt has the highest thermal resistance making it a better choice for high temperature condition as compared to Nickel.

3.1.1 Cobalt

The following was observed when thermal analysis was performed on this material: When cobalt was subjected to a temperature of 500ºC, it was observed that, the heat flow has higher order in a section close to the centre, and less heat flow in the trailing and leading edge of the turbine blade. The total heat flux maximum value 0.092639 was not reached and minimum value 7.1936e-10 in the Center. Which implies that there less temperature order in the centre and higher temperature order at the trailing edge and leading edge of the turbine blade [22]. When cobalt was subjected to a temperature of 1000ºC, it was observed that heat flow has higher order in the centre and less heat flow is obtained in the trailing and leading edge of the turbine blade and the total heat flux maximum value 0.18782 was not reached and minimum value 4.1659e-9. This implies that there less temperature order in the centre and higher temperature order at the trailing edges and leading edges of the turbine blade [22]. When cobalt was subjected to a temperature of 1500ºC, it was observed that heat flow has higher order in the centre and less heat flow is obtained in the trailing and leading edge of the turbine blade and the total heat flux maximum value 0.283 was not reached and minimum value 2.2127e-9, which implies that there less temperature order in the centre and higher temperature order at the trailing edges and leading edges of the turbine blade [22].



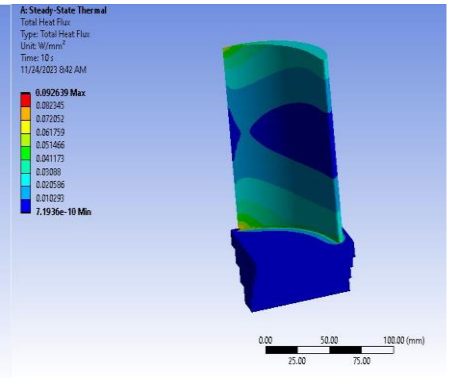
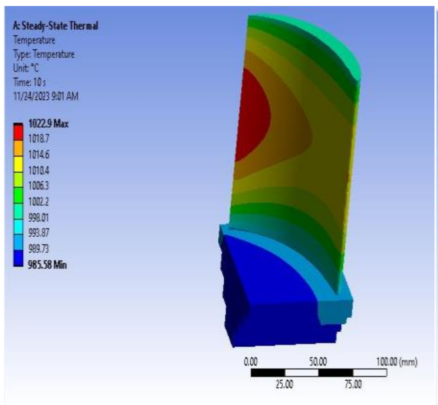


Figure 4. Temperature distribution at 500 Figure 5. Total heat flux at 500



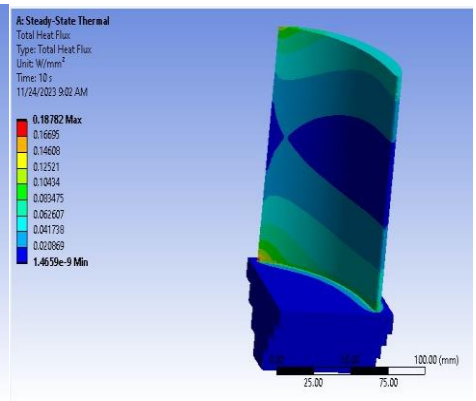
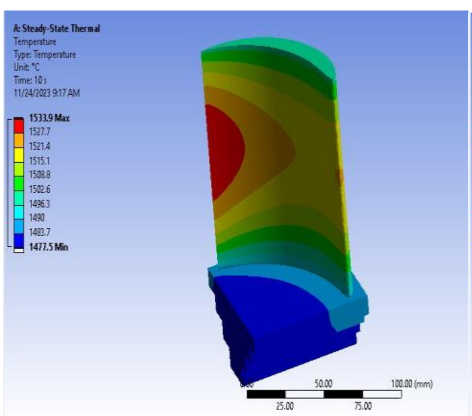


Figure 6. Temperature distribution at 1000 Figure 7. Total heat flux at 1000



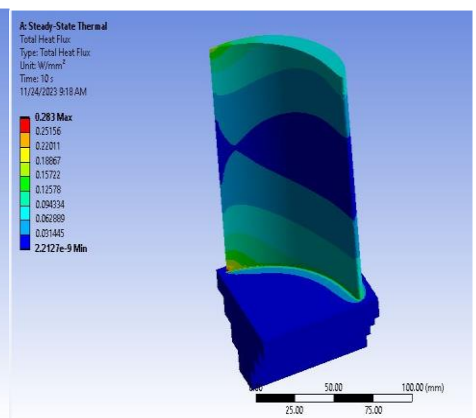
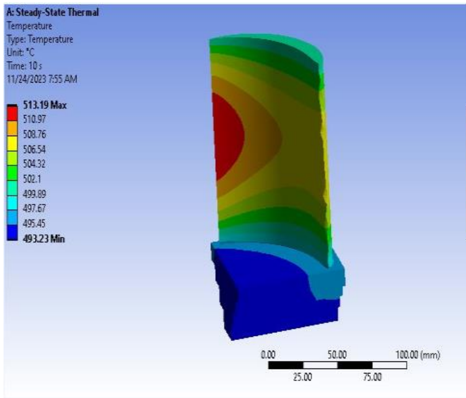


Figure 8. Temperature distribution at 1500 Figure 9. Total heat flux at 1500

3.1.2 Nickel

The following was observed when thermal analysis was performed on this material: When nickel was subjected to a temperature of 500°C, it was observed that heat flow has higher order in the centre and less heat flow is obtained in the trailing and leading edge of the turbine blade and the total heat flux maximum value 0.067967 was reached at the tailing edge and minimum value 1.5184e-9 around the centre of the turbine blade, which implies that there less temperature order in the centre of the turbine blade and higher temperature order at the trailing edges and leading edges of the turbine blade [11, 23, 24, 25]. When nickel was subjected to a temperature of 1000°C, it was observed that heat flow has higher order in the tip of the turbine blade and less heat flow is obtained in the trailing and of the turbine blade and the total heat flux maximum value 0.11829 was reached at the tailing edge and minimum value 2.36294e-9 around the tip of the turbine blade. This implies that there less temperature order in the tip of the turbine blade and higher temperature order at the trailing edges of the turbine blade [23].



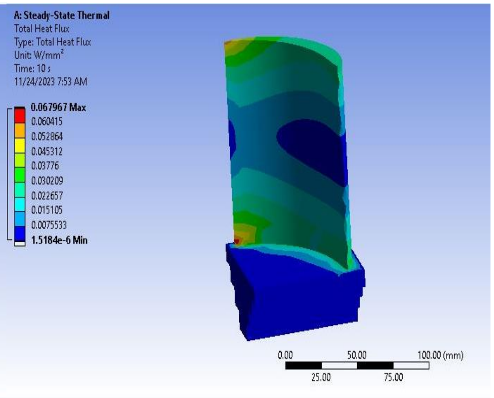
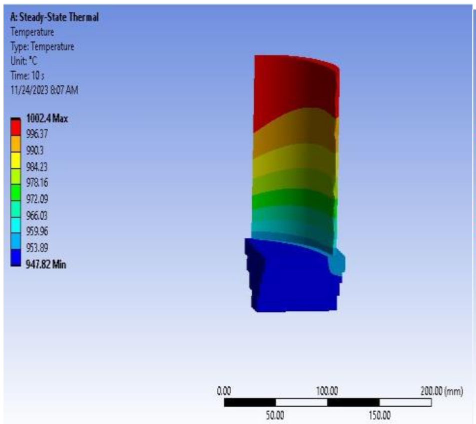


Figure 10. Temperature distribution at 500 Figure 11. Total heat flux at 500



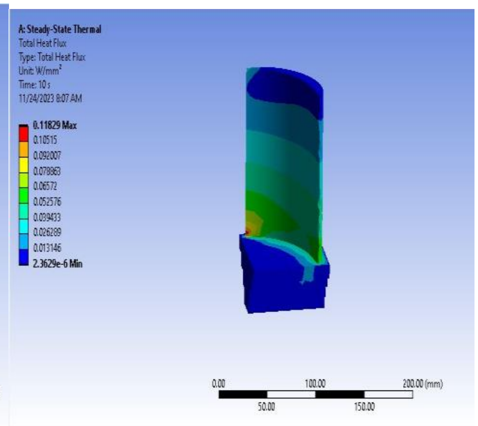
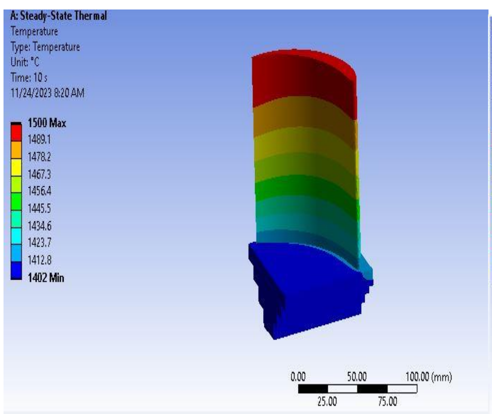


Figure 12. Temperature distribution at 1000 Figure 13. Total heat flux at 1000



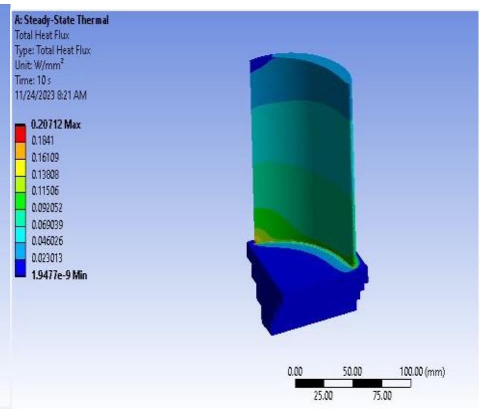


Figure 14. Temperature distribution at 1500 Figure 15. Total heat flux at 1500

3.2 THERMAL BOUNDARY CONDITION

Thermal boundary conditions are used to describe the behavior of heat transfer at the interface between different materials. Three boundary conditions were used namely Heat flow, Temperature and Convection were applied on the turbine blade model. In the convective boundary condition, the convective heat transfer coefficient (h) and temperature of surrounding gases (T) must be specified on the areas subjected to convection. Temperature boundary condition include constant temperature, known temperature and heat flux. Heat flow boundary condition plays a crucial role in heat transfer analysis, and they are used to define the behavior of heat at the boundaries of a system whether through temperature, heat flux or convection boundary conditions. It was observed from the graph that all the materials can withstand temperature of 1500C but some part of the turbine blade will start melting before reaching 1500. These lines represent the turbine blade parts during thermal analysis. It was observed that nickel started melting from the tip of the blade and cobalt from the root of the turbine blade. Cobalt has a promising potential with a thermal resistance of 1495°C and can withstand more heat.

Table 2. Results for the thermal analysis of the proposed materials

Materials	Temperature	Maximum Temperature	Minimum temperature	Maximum total heat flux	Minimum total heat flux
cobalt	500	511.82	493.7	0.092639	7.1936e-10
	1000	1022.9	985.58	0.18782	1.4659e-9
	1500	1533.9	1477.5	0.283	2.2127e-9
Nickel	500	513.19	493.23	0.067967	1.5184e-6
	1000	1002.4	947.82	0.11829	2.3629e-6
	1500	1500	1402	0.20712	1.9477e-9

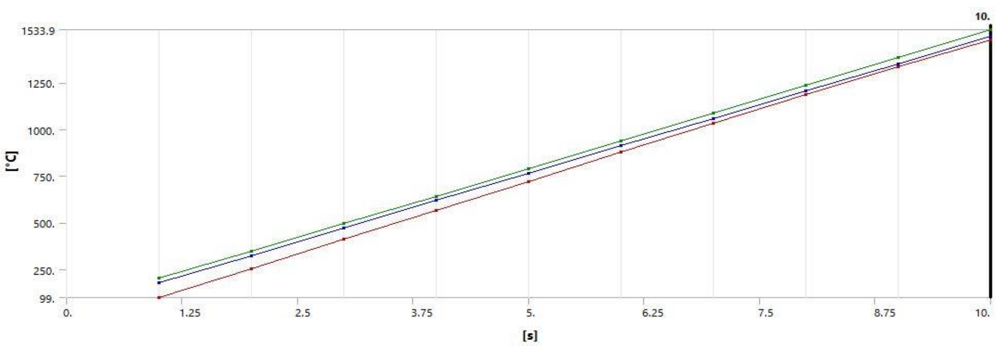


Figure 15. Temperature against time for cobalt at 1500

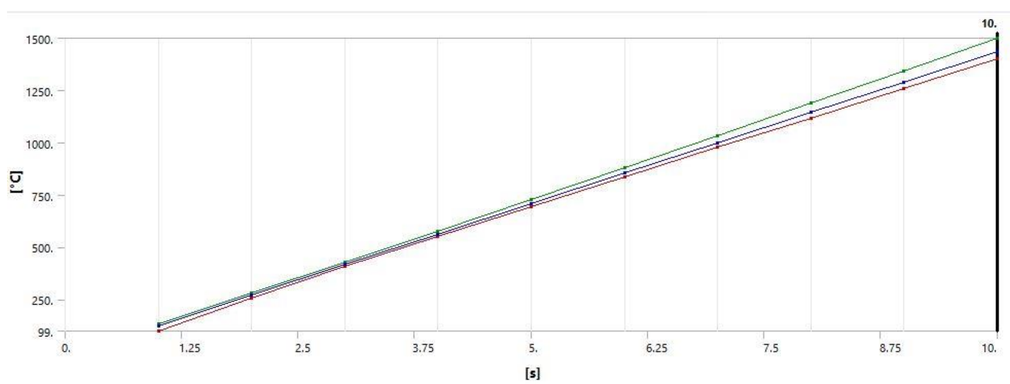


Figure 16. Temperature against time for nickel at 1500C

4 CONCLUSIONS

The selection of turbine blade materials is a critical aspect of turbine design, particularly in the context of thermal considerations. The thermal analysis of turbine blades involves the investigation of heat transfer and temperature distribution within the blade, considering factors such as thermal conductivity, mechanical strength, and compatibility with the working fluid to prevent corrosion. In this investigation, ANSYS was used to perform thermal analysis on various temperature condition at 500, 1000, 1500 on

Cobalt and Nickel. All the material withstood temperature of more than 1000 ^{0}C but no material was able to withstand up to 1500 ^{0}C. From the thermal analysis of nickel and cobalt at various temperature conditions. Cobalt has superior thermal properties with high thermal conductivity desirable for turbine blades as it can efficiently dissipate the heat generated by the gas stream from the combustor. Materials with higher thermal conductivity and higher total heat flux can be used as turbine blade materials to improve the thermal efficiency of the Gas Turbine engine. Further research and development in this area could lead to the continued development and advancement of cobalt-based alloys for turbine blade applications.

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