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Mechanical and Thermal Performance of Ceramic and Nickel Superalloys Composites for Gas Turbine Blade Applications

Georgios KARADIMAS, Konstantinos GEORGARAKIS, and Konstantinos SALONITIS
School of Aerospace, Transport, and Manufacturing, Cranfield University, Cranfield MK43 0AL, UK.

Abstract. Turbines transform thermal energy into work. Traditionally nickel superalloys are used for the turbine blades. In the present paper five ceramic matrix composite materials are investigated as alternatives. The first phase of a rotor blade gas turbine has been structurally and thermally examined in the current work using Finite Element Analysis. The thermal behaviour, as well as the mechanical performance brought on by centrifugal, tangential, and axial forces are calculated. The results indicate which materials can withstand the highest amount of stress under specific thermal and mechanical loads and will indicate which material will have a greater life expectancy.

Keywords. CMC materials, Nickel Superalloys, Composites, Thermal analysis, Structural analysis.

1. Introduction

One of the design objectives when developing turbines is to increase the operating temperature since such an increase result in higher engine efficiency. Additionally, the power-to-weight ratio is a significant feature of gas turbines [1]. The turbine blades should be built so that the steam passage across their surface generates more rotational energy. The goal of turbine blades is to extract energy from hot gases, and creep is regarded as the primary cause of turbine blade failure [2]. The service life of such gas turbine components is affected by their wear, corrosion, fracture, and deformation during their life cycle [3]. If a problem occurs in the turbine section, it will substantially impact the overall engine function and, evidently, the safety of the gas turbine engine [4, 5]. Such damage mechanisms limit the life of ceramic materials under dynamic loads.

The turbine's operating temperature, known as the firing temperature, also influences efficiency, with greater temperatures resulting in better efficiency [2]. However, the thermal conditions the turbine blade metal alloy can withstand limit the turbine inlet temperature. Gas temperatures at the turbine inlet range from 1200ºC to 1600ºC; however, unusual conditions and overloading have resulted in inlet temperatures as high as 1600ºC, resulting in fatigue and blade fracture [6].

The present study presents a case study of oxide and non-oxide ceramic matrix composite (CMC) materials versus nickel superalloys currently used in rotor gas turbine blades using Finite Element Analysis. Thermal and structural analyses with and without thermal loads were undertaken. The output findings compare the average temperatures, deformation, and von Mises stresses, allowing the selection of blade materials.

2. Gas Turbine Blade Materials

Due to their harsh operating conditions, materials used in modern gas turbines are in the forefront of the state of the art [7]. Turbine inlets are under the most challenging conditions operating under extreme temperatures (1400^{O}C - 1500^{O}C), with high pressure, high rotational speed, vibration, small circulation area, and so on [8].

Iron, nickel, and cobalt are the most common materials utilized in the production of blades, with chromium serving as a primary alloying element due to its excellent oxidation resistance [9]. Timken alloys, Hastelloy, Nimonic alloy, and Inconel are the most often used alloys [10]. According to previous case studies Inconel 625, and Hastelloy X are the most used superalloy materials for such applications [11]. Both material mechanical and thermal properties are listed in Table 1.

Materials	Inconel 625	Super Alloy Grade X	Al_2O_3/B_4C (50%Vf)	SiC/SiC (35-45%Vf) Woven Laminate	Al_2O_3/SiO_2 (Nextel 720) Woven-Fabric
Youngs Modulus (GPa)	208	210	382	199.5	143.5
Density (kg/m^3)	8440	7780	3310	2900	2600
Poisson's Ratio	0.29	0.3	0.21	0.19	0.2
Thermal Conductivity (W/mK)	21.3	22	23	13.5	3.495
Thermal Expansion Coefficient ($\mu m/\boldsymbol{m}$℃)	13.1	10	5.3	4.295	1.95
Yield Strength (MPa)	1150	1175	517	294	208.5
Melting Temperature (℃)	1350	1370	2100	2050	1800

Table 1 Properties of selected materials (the first two are nickel superalloys and the rest are CMCs) [15].

The use of ceramics for turbine blades is also being studied, and research is being conducted on this subject [9]. Materials that work under high loads and temperatures have different creep rates, resulting in variable strains. These cause a gradual change in blade morphology over time, with the blades filling the original gap at their tips. Failure occurs because of this contact with the casing.

Because of their light weight, high strength and toughness, and high-temperature capability, ceramic matrix composites are also considered. For many years, research has focused on fibre-reinforced ceramics, unlike monolithic materials, which have appropriate strength at high temperatures but suffer from poor impact resistance [10]. Today's ceramic composites use silicon carbide fibres in a ceramic matrix, such as silicon carbide or alumina [12]. These materials can operate with no additional cooling at temperatures of up to 1200°C, which is slightly higher than what coated nickel alloy systems can achieve. To sustain long-term stability at the highest temperatures in an oxidizing atmosphere, uncooled turbine applications will require an oxide-oxide ceramic material system [13]. Alumina fibres in an alumina matrix are an early example of such a system. Single crystal oxide fibres, which can work at temperatures of 1400°C, can be employed to achieve the greatest load-carrying capacities at high temperatures.

Two oxide and one non-oxide CMC materials have been selected for the present study (Table 1). They were selected based on the approach presented by the authors in [12,13]. The criteria for the material selection considered the aerospace applications' material requirements with regards to their mechanical, physical, and chemical properties, such as high strength, stiffness, fatigue durability, damage tolerance, low density, high thermal stability, high corrosion, and oxide resistance. Commercial criteria such as cost, servicing, and manufacturability were also considered [13, 14].

3. Gas Turbine Blade Model

To examine the damage mechanisms of different nickel superalloy and CMC materials, a gas turbine blade design was built and simulated in ANSYS software (Figure 1). The gas turbine blade is analyzed under two stress categories. The first type is centrifugal stresses caused by angular speeds in the blade, and the second is thermal stresses caused by temperature gradients within the blade material.

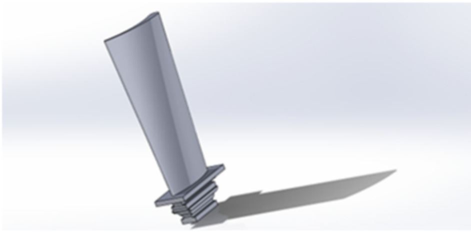

Figure 1 Gas turbine blade design.

To analyze the distribution of applied loads, deformation, temperature, and other consequences during component service, all degrees of freedom (DOF) of a root must be captured. The main loads acting on the blade include gas pressure and force due to momentum change, which permits the blade to revolve.

The Gas turbine blade is fixed to the rotor. The half of the gas turbine blade root is fixed inside the rotor, so the displacement boundary conditions applied to the half of the blade root can be determined as $U_x = U_y = U_z = 0$ and the rotations of all the same nodes are constrained, $R_x = R_y = R_z = 0$. For the rotor blade, the forces components are assumed to be; the axial component: $F_a = 500$ N, for tangential: $F_t = 15$ N, and the centrifugal one: Fc = 1400 N, similar to the values found in literature for FEA stress analysis [9]. Moreover, an axial rotational velocity of 200rad/s and a tangential coordination $r_{hub} = -0.3345$ in the turbine blade is assumed. The tangential coordination was calculated by measuring the distance from the center point of the Jet-A1 combustor liner inlet ($R=\frac{\pi}{4}(D^2 - d^2)$) and then assuming that $r_{hub}=1.5R$ [16].

For the thermal analysis on the gas turbine blade, a maximum of 1200°C is applied on the blade structure as the lower melting point of the comparing materials. A root temperature of 300°C is applied on the rotor of the turbine blade. Moreover, a film coefficient h=464.7 W/m^2C is added to the blade, which is a common value used for computational simulations of rotor blades according to the literature. [17,18]

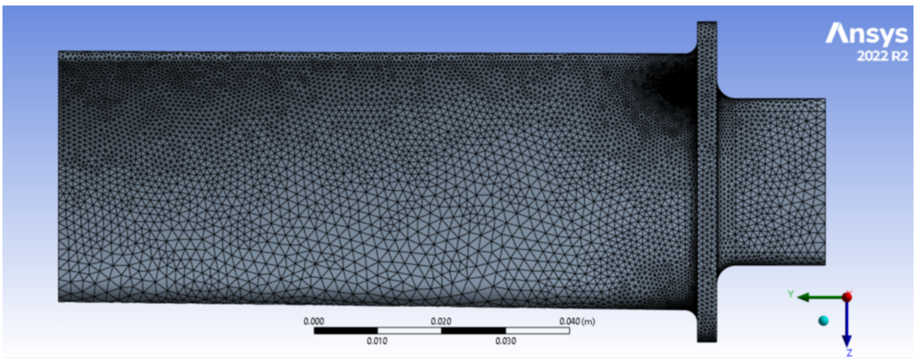

Figure 2 Meshing profile of gas turbine blade model.

For the meshing of the blade, six different grid profiles were tested, with every subsequent mess having 20% finer elements. The final messing was selected where further refinement does not change the predictions by more than 2%. Tetrahedral meshing (curvature and proximity-based) with a constant grow rate of 1.05m was used. The impact of the meshing on the calculations can be seen in Figures 3 and 4.

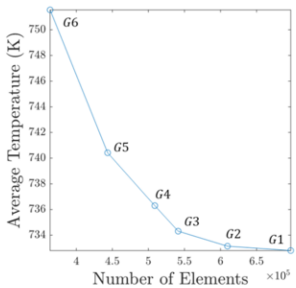

Figure 3 Average Temperature vs Number of Elements grid analysis results.

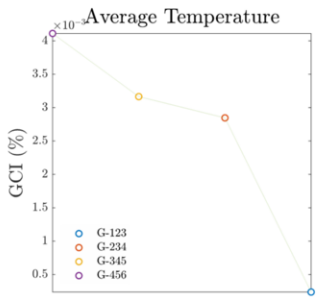

Figure 4 GCI VS Average Temperature analysis results.

4. FEA Thermal and Structural Analysis

Three analyses were carried out for each material: a thermal analysis and two static structural analysis, one with the applied thermal load and one without it. The maximum and average temperatures, stresses, and deformations of each different material were calculated and compared as it can be seen in Tables 2 and 3.

Material	T_{max} (°C)	T_{Avg} (°C)	σ_{max} (MPa)	σ_{Avg} (MPa)	ε_{max} (mm)	ε_{min} (mm)
Inconel 625	1200	734	232.6	28.2	0.80	0.066
Hastelloy X	1200	726	226.38	28.0	0.80	0.066
Nextel 720	1200	843	247.24	28.1	1.16	0.096
Al_2O_3/B_4C	1200	664	247.00	28.1	0.44	0.036
SiC/SiC	1200	711	248.53	28.2	0.83	0.070

Table 2 Thermal and Static Structural without thermal load results.

Material	σ_{max} (MPa)	σ_{Avg} (MPa)	ε_{max} (mm)	ε_{min} (mm)
Inconel 625	6282	1361	1.8	0.25
Hastelloy X	6631.9	1474	1.9	0.27
Nextel 720	769.23	164.5	1.175	0.12
Al_2O_3/B_4C	4492	906	0.79	0.103
SiC/SiC	1922.8	390	0.96	0.105

Table 3 Static Structural analysis results with thermal load results.

Figure 5 Thermal analysis of gas turbine blade.

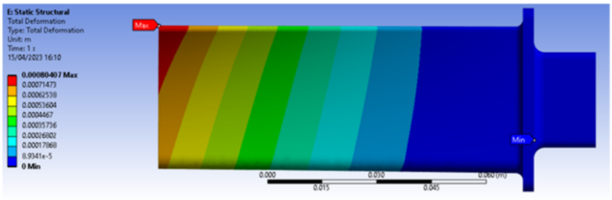

Figure 6 Deformation analysis without thermal load.

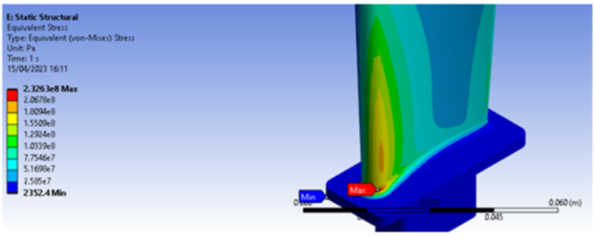

Figure 7 Stress analysis without thermal load.

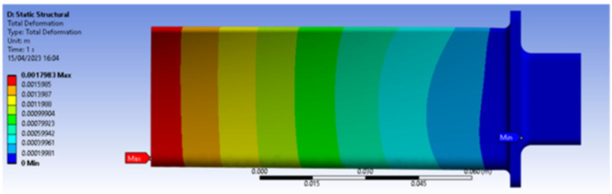

Figure 8 Deformation analysis with thermal load.

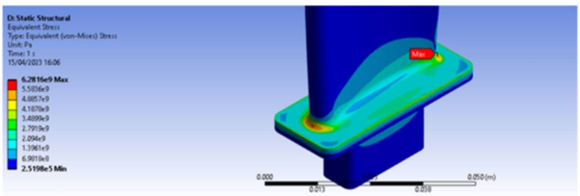

Figure 9 Stress analysis with thermal load.

It can be observed that all selected materials share a maximum temperature of 1200℃. The average temperature varies for each material. Al_2O_3/B_4C and SiC/SiC CMCs showcase lower average temperatures when exposed to 1200°C. This suggests they can effectively mitigate the heat transfer from the hot gas environment to the blade structure. It also indicates that such CMCs have a higher thermal resistance and lower thermal conductivity than nickel superalloys, retaining their cooler temperature under the given operating conditions, minimising heat transfer to the blade structure, and reducing the potential for thermal stresses and material degradation.

Inconel 625 and Hastelloy X demonstrate lower maximum and average stresses compared to Nextel 720, Al2O3/B4C, and SiC/SiC when there is no thermal load applied at the blade structure, demonstrated in Figure 7. This suggests that Inconel 625 and Hastelloy X are better able to withstand the applied loads without exceeding critical stress limits. In terms of deformations, Nextel 720 exhibits the highest maximum deformation, followed by SiC/SiC, Inconel 625, Hastelloy X, and Al2O3/B4C. Similarly, Nextel 720 and SiC/SiC also display larger minimum deformations (showcased in Figure 6) compared to the other materials.

In contrast, Table 3 results indicate the mechanical responses of each material when subjected to the applied thermal loads. The stress values represent the internal forces experienced by the materials (Figure 9), while the deformation values indicate the strain they undergo (Figure 8). It can be observed that Inconel 625 and Hastelloy X demonstrate higher maximum and average stress values compared to Nextel 720, Al2O3/B4C, and SiC/SiC. This suggests that Inconel 625 and Hastelloy X experience greater internal forces and are subjected to higher stress levels under the given thermal conditions. In contrast, Nextel 720, Al2O3/B4C, and SiC/SiC exhibit lower stress values, indicating that these materials can withstand the applied thermal loads with less stress. Similarly, the maximum and minimum deformations of the CMC materials (Nextel 720, Al2O3/B4C, and SiC/SiC) are lower than those of Inconel 625 and Hastelloy X. This implies that the CMC materials exhibit lower deformation or strain when subjected to the applied thermal loads.

These lower stress and deformation values in the CMC materials can be beneficial for the gas turbine blade's performance and lifespan. Lower stresses help to minimize the risk of material failure, while lower deformations contribute to improved structural integrity and dimensional stability. By using CMC materials with lower stress and deformation characteristics, it is possible to enhance the blade's reliability, reduce the likelihood of fatigue or creep-related issues, and potentially extend the component's operational life.

5. Conclusion

The structural and thermal finite element study of the first stage gas turbine blade was performed. The goal of this investigation was to explore the component life in terms of individual and cumulative damage criteria of existing superalloy materials against CMC materials. This would assist in determining which material is preferable based on better performance outcomes.

Turbine applications require materials that keep the temperature as low as possible to maximise the creep life and minimise deformations. From the stress analysis, the materials with lower stress allow for lower minimum and maximum fatigue cycles, which results in higher fatigue life of the application. Furthermore, from the temperature analysis, it was concluded that the lower the temperature, the less cooling air is required. This allows for better overall engine performance.

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