

Degradation and Fatigue Life Methods for Ceramic Matrix Composite and Nickel Superalloy Materials in Gas Turbine Combustor Liner

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Abstract. This paper investigates the durability of Ceramic Matrix Composite (CMC) and Nickel Superalloy materials in gas turbine combustor liners across different flight conditions. Thermo-mechanical and physical properties of CMCs are assessed and compared with selected superalloys (i.e., Inconel 625, Hastelloy X, SiC/SiC, Al₂O₃/B₄C, and Al₂O₃/SiO₂) using Finite Element Analysis (FEA). An integrated methodology employing Computational Fluid Dynamics (CFD) and FEA is introduced to analyze thermal stresses and fatigue life, establishing a direct connection between combustion dynamics and structural responses. The study addresses a research gap by thoroughly evaluating CMC materials in gas turbine combustor liners, offering valuable insights for material selection and design strategies in aerospace engineering. The findings enhance understanding of CMC behavior, showcasing their reliability and durability for gas turbine components and their usage for advancements in aerospace applications.

Keywords: Ceramic Matrix Composites (CMCs), Nickel Superalloys, Aerospace applications, Durability assessment

1 Introduction

Increasing combustor operating temperatures is crucial to improve gas turbine thermodynamic efficiency [1]. This requires ensuring that parts like turbine blades and combustor liners can withstand high temperatures for extended periods of time. Furthermore, understanding how long these parts will last is crucial for designing turbines and planning maintenance [2].

While existing research in this field mostly focuses on gas turbine blades due to their exposure to severe mechanical stresses from high rotational speeds [3,4], limited attention has been given to combustor liners. More specifically, literature on combustors

often emphasises fluid dynamics and combustion process optimisation, whereas research on predicting thermal loading on combustor liners is notably limited.

Two primary methods have been used to enhance gas turbines design. One method investigates how engines behave during flights to predict the lifespan of parts [5,6]. This approach analyzes flight data to understand engine performance, using specialized software tools to estimate when parts will wear out. Another method, which uses computational fluid dynamics (CFD), helps predict the performance of the combustor [7,8]. By simulating airflow in the combustor, temperatures and combustion efficiency can be predicted. This aids in designing better combustors and prolonging turbine lifespan.

However, there's still a gap in the literature regarding the degradation and lifespan impact of diverse flight profiles on engine component deterioration and direct comparisons between Ceramic Matrix Composites (CMCs) and metallic components. Most studies focus on metal parts, especially nickel alloys, with limited exploration of ceramic composite. Further investigation of CMCs can lead to better airplane material choices, improving engine efficiency and durability.

Understanding the behavior of Ceramic Matrix Composites (CMCs) under various flight conditions and comparing them with nickel alloys is key to enhancing turbine blade design, maintenance, and efficiency. CMCs, being lighter, stronger, and more heat-resistant than nickel alloys, may perform differently under flight conditions, affecting their durability and effectiveness. This study explores how CMCs react in different flight scenarios, providing insights crucial for improving turbine design and maintenance for aerospace applications.

2 Materials and Methods

Gas turbine combustor liners require the utilization of a systematic approach due to thermal stresses from combustion dynamics and fluid flow. This study uses Computational Fluid Dynamics (CFD) to analyze air and flue gas behavior and Finite Element Analysis (FEA) to evaluate the liner structural and thermal responses.

Due to the combustor's complex geometry, modeling focuses on one-sixteenth of its size to capture essential flow characteristics while managing computational efficiency.

Material selection for aerospace applications involves evaluating mechanical and thermal properties [9]. Non-oxide Ceramic Matrix Composites (CMCs) like SiC/SiC offer high strength and thermal shock resistance, while oxide CMCs like $\text{Al}_2\text{O}_3/\text{SiO}_2$ and $\text{Al}_2\text{O}_3/\text{B}_4\text{C}$ provide thermal insulation and oxidation resistance [10,11]. These materials are compared with nickel superalloys Inconel 625 and Hastelloy X, known for their robust properties in aerospace applications [12].

Model development includes dimensional specifications based on combustor liner temperature and pressure data [13], followed by CAD modeling and meshing analysis refinement.

The mesh density of the model is adjusted for computational accuracy, with a balance between resources and precision. Reaching convergence when results stabilize within a 2% threshold. The type of meshing used is hexahedral and includes 558,090 mesh cells.

For the flight profile phases, including rejected take-off (RTO), top of climb (ToC), and maximum continuous rating (MCR), a set of boundary conditions in Computational Fluid Dynamics (CFD) are implemented, with total and static pressures, and Mach numbers, and output pressures utilized for structural analysis in Finite Element Analysis (FEA). Finally, the number of cycles to failure is calculated using fatigue life methods for different materials.

3 Combustor Liner Modeling

The fluid dynamics analysis of the combustor liner was conducted using ANSYS Fluid Flow (Fluent) CFD software. For the model, pressure and temperature were applied for greater accuracy. At the inlet, gas temperature and gauge total pressure P were determined from flight profiles, adjusting supersonic gauge pressure p using a compressibility equation to account for Mach number M effects.

$$p = P / (1 + 0.2 * M^2)^{3.5} \quad (1)$$

Turbulence was modeled using the Shear-Stress Transport (SST) k - ω model, ensuring insights into flow patterns and heat transfer.

Outlet conditions were set based on flight profile data for accurate pressure and flow distribution. Moreover, the combustor liner walls were assumed to be stationary, featuring a non-slip condition and standard wall roughness to mimic surface texture. Air properties were specified using an ideal gas model with constant values for efficiency.

Boundary layer analysis was determined to calculate the wall temperature and heat transfer coefficient using velocity at the boundary layer's displacement thickness, using equation 2.

$$h = 12.12 - 1.16 * V_m + 11.6 \sqrt{V_m} \quad (2)$$

Symmetry planes simplified gas volume analysis, while an inverse projection method accurately determined boundary layer thickness. An inverse projection method was used for lines not perpendicular to the wall to accurately determine the boundary layer thickness volume for accurate thermal analysis. Film coefficient and velocity magnitude variations across flight scenarios impacted burner conditions, cooling, combustion, and pressure profiles. Convergence was achieved after 3000 iterations.

After attaining the CFD results the FEA model accurately imported combustor liner geometry, incorporating material properties for SiC/SiC, Al₂O₃/SiO₂, Al₂O₃/B₄C, Hastelloy X, and Inconel 625 from material libraries [14]. Boundary conditions replicated temperature distributions and convection based on prior CFD simulations, with

supersonic gauge pressure calculated using Equation 4 for each flight profile, which relates pressure (p) to total pressure (P), fluid density (ρ), Mach number (M), and specific heat ratio (γ).

$$p = \frac{P}{(1 + \frac{\gamma-1}{2} M^2)^{-\frac{\gamma}{\gamma-1}}} \quad (3)$$

After applying the calculated pressure results and CFD boundary condition results, the stress, strain, and deformation for each flight profile are calculated for the selected materials as seen in fig 1. Table 1 depicts the FEA results for stress, strain, and deformation.

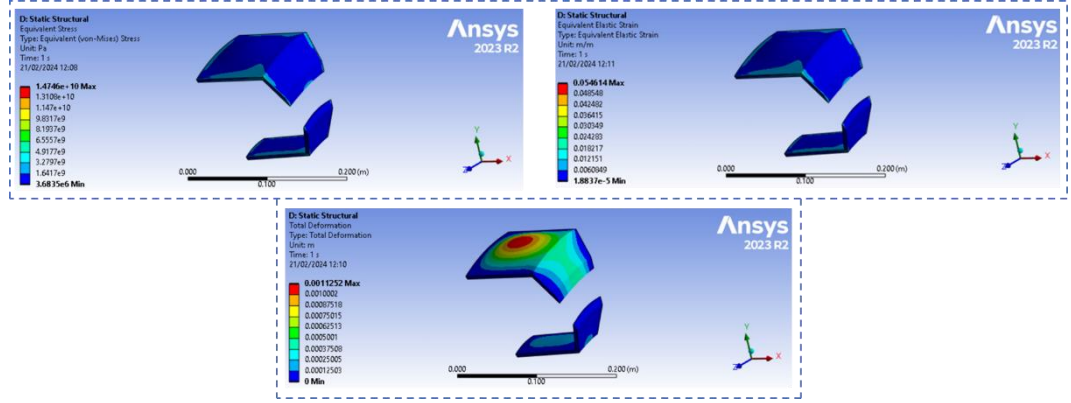


Fig. 1 Stress, strain, and deformation results representation.

Table 1. FEA results for MCR, ToC, and RTO flight conditions.

Materials	Stress (GPa)			Strain (m/m)			Deformation (m)		
	MCR	ToC	RTO	MCR	ToC	RTO	MCR	ToC	RTO
Inconel 625	28.994	31.232	35.7	1.582	1.62	1.65	0.02676	0.029	0.033
Hastelloy X	32.833	35.4	40.42	1.6	1.67483	1.73	0.029261	0.032	0.036
SiC/SiC	12	12.9	14.8	0.0444	0.0478	0.0546	0.00947	0.0103	0.0112
Al2O3/B4C	19.6	21.1	24.1	0.0494	0.0533	0.061	0.007	0.0116	0.0137
Al2O3/SiO2	7.65	8.25	9.45	0.0551	0.0593	0.068	0.0121	0.0131	0.0165

Inconel 625 and Hastelloy X exhibit higher strain values than SiC/SiC, Al2O3/B4C, and Al2O3/SiO2 in all flight conditions due to their greater ductility and lower stiffness, allowing them to absorb more energy before failing. Conversely, SiC/SiC, Al2O3/B4C, and Al2O3/SiO2 show lower strains, maintaining structural integrity better because of their higher stiffness and lower ductility.

4 Fatigue Life Assessment

4.1 Fatigue Life Analysis

Predicting fatigue life is crucial in aerospace applications. Using previously calculated FEA results and parameters, such as: stress amplitude, mean stress, and strain, established methods like Goodman's, Soderberg's, and Coffin-Manson's guide life estimations based on specific conditions and material properties. The Coffin-Manson model, important for analyzing fatigue failures through plastic strain amplitude, and the Basquin model, which details stress amplitude-fatigue life relationships for nickel superalloys and CMC materials, allow for accurate fatigue life predictions. The combined equation for total life is presented in Equation 4.

Coffin-Manson equation:

$$\frac{\Delta \varepsilon}{2} = \frac{\sigma'_f}{E} (2N_f)^b + \varepsilon'_f (2N_f)^c \quad (4)$$

Constants b and c , derived from previous literature, ensure reliability based on established experimental data [19]. These constants, initially for nickel superalloys, are applied to all selected materials due to limited evidence for equivalent CMCs. By using the material constants and FEA stress and strain results, the amplitude stress and strains were calculated and used in the equations above for each selected material.

4.2 Results

This study applied fatigue analysis techniques to both superalloys and ceramic matrix composites (CMCs) to assess their fatigue behavior. Due to uncertainties in CMC material constants, a uniform approach was adopted using nickel alloy with different constant variations for all materials [19], as seen in Table 3 below.

Table 2. Different variations of c and b constants from Coffin-Manson equation.

Case Study	A	B	C
c	-0.2	-0.4	-0.6
b	-0.01	-0.07	-0.08

To estimate the number of cycles to failure (N_f) the data provided from table 1 and 2 was used. Three different cases were created by changing the constants b and c as seen in table 6 below. A root-finding algorithm was employed, using equations 5 and 6 below, for calculating the life cycle results for each flight condition for the three different cases [20, 21].

$$f_{(Nf)} = \frac{\Delta \varepsilon}{2} - \frac{\sigma' f}{E} (2Nf)^{-b} - \varepsilon' f (2Nf)^{c-b} \quad (5)$$

$$N_{fi+1} = N_{fi} - \frac{f(N_{fi})}{f'(N_{fi})} \quad (6)$$

Inputting data into the fatigue life prediction model determines N_f values for each material under varying conditions, offering insights into durability. Fatigue life cycles, crucial for assessing material endurance under cyclic loading, are influenced significantly by constants c and b . Figure 2 illustrates N_f results from three case studies where these constants were adjusted.

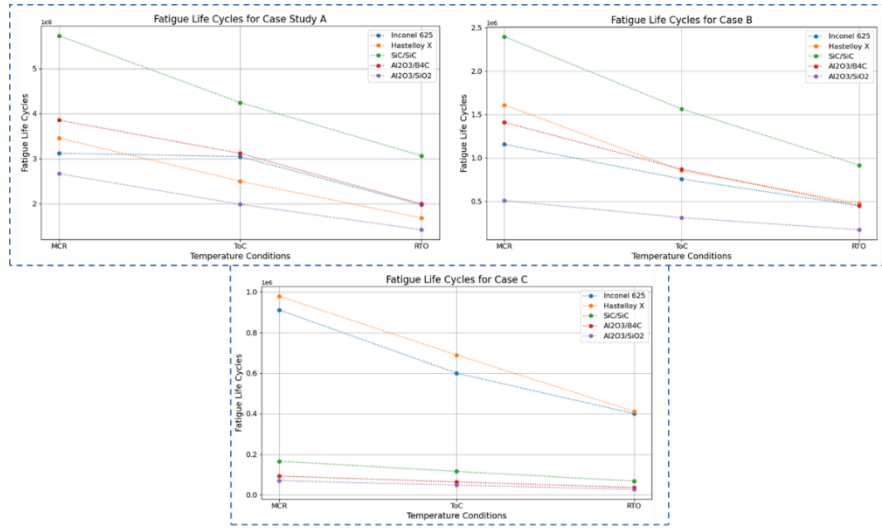


Fig. 2 Fatigue life cycle results for cases A, B, and C.

Table 3 Fatigue life results ($\times 10^3$) for Cases A, B, and C

Materials	Case A			Case B			Case C		
Flight Profiles	MCR	ToC	RTO	MCR	ToC	RTO	MCR	ToC	RTO
Inconel 625	3123	3046	1979	1155	756.2	447.2	912.2	600.5	400.9
Hastelloy X	3456	2501	1687	1609	852.3	473.6	980.1	690	412.1
SiC/SiC	5724	4244	3066	2395	1562	915.5	166.3	115.8	68.03
Al2O3/B4C	3854	3117	1999	1408	869.1	448.1	92.88	63.71	36.24
Al2O3/SiO2	2668	1989	1426	507.7	311.1	170	70.15	48.23	27.02

Three case studies (A, B, and C) were conducted, each with different combinations of these constants. In Case Study A ($c=-0.2$, $b=-0.01$), SiC/SiC and Al2O3/B4C showed high fatigue resistance, with subtle fluctuations affecting Hastelloy X. In Case Study B

($c=-0.4$, $b=-0.07$), fatigue life cycles decreased across all materials compared to Case A, notably for Hastelloy X and SiC/SiC. Case Study C ($c=-0.6$, $b=-0.08$) exhibited similar trends to Case B, indicating even lower fatigue life cycles, especially for SiC/SiC and Al₂O₃/B₄C. Changes in constants influenced fatigue performance and highlighted the sensitivity of models. More specifically, higher values of c and b correlated with reduced fatigue life cycles, illustrating the relationship between material properties, operational environments, and fatigue life predictions.

5 Conclusion

This study uses CFD and FEA analyses to evaluate Nickel Superalloys and Ceramic Matrix Composites (CMCs) for gas turbine combustor liners. The results demonstrate CMCs' superior mechanical and thermal properties over superalloys. Due to their lower density, CMCs also facilitate lighter structure designs with comparable performance, a critical advantage in aerospace for boosting fuel efficiency and performance. Future research could enhance CMC performance and durability through improved material qualities and microstructural engineering, potentially extending the lifespan and effectiveness of gas turbines.

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