**E-ISSN:** 2707-4552
**P-ISSN:** 2707-4544
IJMTME 2024; 5(1): 32-36
Received: 25-12-2023
Accepted: 29-01-2024

**Tetsuya Ohmagari**
Department of Mechanical Engineering, School of Engineering, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro, Tokyo, 152-8552, Japan

**Norio Suzuki**
Department of Mechanical Engineering, School of Engineering, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro, Tokyo, 152-8552, Japan

# Analysis of thermo-mechanical fatigue in high-temperature superalloys for gas turbine applications

**Tetsuya Ohmagari and Norio Suzuki**

## Abstract

This paper presents a comprehensive analysis of thermo-mechanical fatigue (TMF) in high-temperature superalloys used in gas turbine applications. TMF is a critical factor affecting the lifespan and performance of gas turbine components, which operate under cyclic thermal and mechanical loads. This study investigates the mechanisms of TMF, the material properties of superalloys that influence their fatigue behavior, and the methods for evaluating and mitigating TMF damage. Advanced characterization techniques and computational modeling approaches are employed to gain insights into the fatigue mechanisms and predict the lifespan of turbine components.

**Keywords:** Gas turbine applications, turbine components, thermo-mechanical fatigue, temperature superalloys

## Introduction

Gas turbines are essential in power generation and aerospace industries due to their high efficiency and power output. These turbines operate under extreme conditions, involving high temperatures and cyclic mechanical loads, which pose significant challenges to the materials used in their construction. One of the critical components of gas turbines is the turbine blades, which are typically made from high-temperature superalloys. These superalloys, primarily based on nickel, cobalt, and iron, are chosen for their exceptional mechanical strength, resistance to creep, oxidation, and corrosion at elevated temperatures.

Thermo-mechanical fatigue (TMF) is a predominant failure mechanism in gas turbine blades, resulting from the cyclic thermal and mechanical loads they experience during operation. TMF can lead to the initiation and propagation of cracks, ultimately causing the failure of turbine components. Understanding the TMF behavior of high-temperature superalloys is crucial for improving the reliability and longevity of gas turbines.

The mechanisms of TMF in high-temperature superalloys are complex, involving interactions between thermal and mechanical stresses. Key factors influencing TMF behavior include microstructural stability, oxidation resistance, and the interaction between creep and fatigue processes. The microstructural stability of the superalloy, including the distribution and morphology of strengthening phases like gamma prime (γ′ \ gamma 'γ′) precipitates, plays a crucial role in TMF resistance. High-temperature environments can cause oxidation and corrosion, which accelerate crack initiation and propagation. Additionally, the interaction between creep and fatigue under cyclic loading can exacerbate TMF damage.

Experimental methods are essential for evaluating TMF behavior and understanding the mechanisms of fatigue damage. TMF testing machines simulate the cyclic thermal and mechanical loads experienced by gas turbine components, providing valuable data on fatigue life under different conditions. Advanced microscopy techniques, such as scanning electron microscopy (SEM) and transmission electron microscopy (TEM), allow for detailed observation of microstructural changes and crack propagation.

Computational modeling complements experimental methods by providing predictive capabilities for TMF behavior. Finite element analysis (FEA) and crystal plasticity modeling simulate stress distribution, deformation mechanisms, and crack growth under TMF conditions. These models incorporate material properties, microstructural data, and environmental conditions to predict fatigue life and identify critical factors affecting TMF resistance.

Mitigating TMF damage involves several strategies, including material optimization, protective coatings, and component design improvements.

**Corresponding Author:**
**Tetsuya Ohmagari**
Department of Mechanical Engineering, School of Engineering, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro, Tokyo, 152-8552, Japan

Developing new alloy compositions with enhanced microstructural stability and oxidation resistance can improve TMF resistance. Applying thermal barrier coatings (TBCs) and oxidation-resistant coatings protects the underlying superalloy from high-temperature environments. Optimizing the design of turbine components to minimize stress concentrations and thermal gradients further enhances TMF resistance

## Objective

The objective of this study is to analyze the thermo-mechanical fatigue (TMF) behavior of high-temperature superalloys in gas turbine applications to enhance their performance and durability through a combination of experimental and computational approaches.

## Experimental Methods

The experimental methods employed to evaluate the thermo-mechanical fatigue (TMF) behavior of high-temperature superalloys are crucial for understanding the mechanisms of fatigue damage and for developing strategies to enhance the performance and lifespan of gas turbine components.

Thermo-Mechanical Fatigue Testing involves preparing test specimens machined from high-temperature superalloy materials according to standardized geometries to ensure uniformity and reproducibility. Specialized TMF testing machines are used to apply cyclic thermal and mechanical loads simultaneously, with precise control over temperature and mechanical load profiles. Specimens undergo cyclic temperature variations, often ranging from room temperature to service temperatures, with rapid heating and cooling cycles to replicate operational conditions. Cyclic mechanical loads are applied in phase (in-phase TMF) or out of phase (out-of-phase TMF) with the thermal cycles, with varying load amplitudes and frequencies to study different loading scenarios.

Microstructural Analysis is essential for understanding the changes that occur during TMF and identifying fatigue damage mechanisms. Advanced microscopy techniques are used for this purpose. Scanning Electron Microscopy (SEM) is employed to observe the surface morphology and microstructural features of fatigued specimens, providing high-resolution images of crack initiation sites, fracture surfaces, and microstructural changes. Transmission Electron Microscopy (TEM) allows for detailed examination of the internal microstructure at the nanoscale, enabling the study of dislocation structures, precipitate morphology, and other microstructural aspects that influence TMF behavior.

Fractography involves analyzing the fracture surfaces of fatigued specimens to determine the mechanisms of crack initiation and propagation. SEM is commonly used for fractographic analysis, revealing features such as striations, secondary cracks, and oxidation marks. This analysis helps to correlate observed fracture features with specific loading conditions and material properties, providing insights into the failure modes under TMF conditions.

Mechanical Testing includes a range of tests to characterize the mechanical properties of high-temperature superalloys, such as tensile tests, creep tests, and hardness measurements. These tests provide baseline data on the material's strength, ductility, and resistance to deformation, which are critical for understanding its performance under TMF conditions. Mechanical testing results are used to calibrate and validate computational models, ensuring accurate predictions of TMF behavior.

High-Temperature Oxidation Testing is performed to evaluate the oxidation resistance of high-temperature superalloys under cyclic thermal conditions. Specimens are exposed to high-temperature environments with controlled oxygen levels to simulate service conditions. Oxidation testing helps to assess the formation of oxide scales, their adhesion, and the impact on the underlying material's mechanical properties. This information is crucial for understanding the synergistic effects of oxidation and mechanical loading on TMF behavior.

Computational Modeling complements experimental methods by providing predictive capabilities for TMF behavior. Finite element analysis (FEA) and crystal plasticity modeling are commonly used to simulate the stress distribution, deformation mechanisms, and crack growth under TMF conditions. Computational models are developed based on experimental data and material properties, allowing for the prediction of fatigue life and the identification of critical factors affecting TMF resistance. These models are validated against experimental results to ensure their accuracy and reliability.

## Computational Modeling

Computational modeling plays a crucial role in understanding and predicting the thermo-mechanical fatigue (TMF) behavior of high-temperature superalloys. It complements experimental methods by providing detailed insights into the material behavior under complex loading conditions and by enabling the prediction of fatigue life and failure modes.

Finite Element Analysis (FEA) is a widely used computational technique for simulating the stress distribution and deformation behavior of materials under TMF conditions. In FEA, the turbine component or test specimen is discretized into small finite elements, each governed by the material's constitutive laws. The thermal and mechanical loads are applied to the model, and the resulting stress and strain distributions are computed. FEA helps in identifying critical regions with high stress concentrations where fatigue cracks are likely to initiate and propagate. It also allows for the simulation of complex geometries and loading conditions that are difficult to replicate experimentally.

Crystal Plasticity Modeling is an advanced approach used to simulate the deformation behavior of materials at the microstructural level. This method takes into account the crystallographic orientation of grains and the interactions between them, providing a more detailed understanding of the material's response to TMF. Crystal plasticity models incorporate the effects of dislocation motion, slip, and twinning, which are critical mechanisms in the deformation of high-temperature superalloys. These models can predict the evolution of microstructural features, such as grain boundary sliding and phase transformations, under cyclic thermal and mechanical loads.

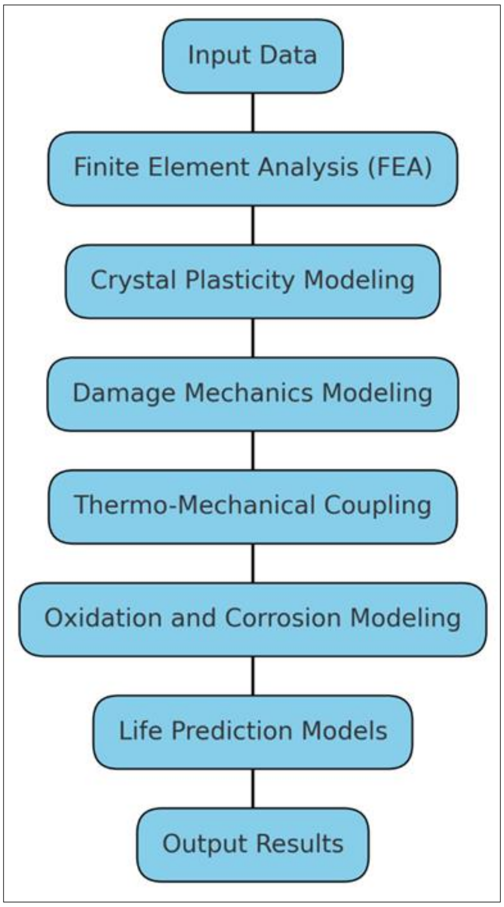
Damage Mechanics Modeling involves the incorporation of damage evolution laws into the computational models to predict the initiation and growth of fatigue cracks. This approach uses continuum damage mechanics (CDM) theories to describe the progressive degradation of the material's mechanical properties due to TMF. The damage variables are integrated into the constitutive equations, allowing for the simulation of crack initiation and propagation based on the local stress and strain states. Damage mechanics models are particularly useful for predicting the fatigue life of components and for assessing the effects of different loading scenarios on TMF resistance.

Thermo-Mechanical Coupling is a critical aspect of TMF modeling, as it captures the interactions between thermal and mechanical fields. Computational models incorporate the effects of thermal expansion, temperature-dependent material properties, and thermal gradients to simulate the coupled thermo-mechanical behavior. This coupling is essential for accurately predicting the stress and strain distributions in components subjected to cyclic thermal and mechanical loads. Thermo-mechanical coupling models help in understanding the synergistic effects of thermal and mechanical stresses on TMF damage.

Oxidation and Corrosion Modeling is used to simulate the effects of high-temperature oxidation and corrosion on the TMF behavior of superalloys. These models take into account the formation and growth of oxide scales on the material surface and their impact on the underlying material's mechanical properties. The oxidation kinetics are coupled with the mechanical stress fields to simulate the interactions between oxidation and fatigue crack growth. This approach provides insights into the synergistic effects of environmental degradation and mechanical loading on TMF resistance.

Life Prediction Models are developed to estimate the fatigue life of turbine components based on the results of computational simulations. These models use empirical or physics-based approaches to correlate the computed stress and strain fields with fatigue life data obtained from experiments. Life prediction models can incorporate factors such as loading frequency, temperature range, and material properties to provide accurate estimates of component lifespan under service conditions. These models are essential for the design and maintenance of gas turbine components, enabling the prediction of service intervals and the prevention of catastrophic failures.

Computational modeling provides a powerful toolset for analyzing the thermo-mechanical fatigue behavior of high-temperature superalloys. By combining various modeling approaches, researchers can gain a comprehensive understanding of the material behavior under complex loading conditions and develop strategies to enhance the performance and durability of gas turbine components.



**Case Study: TMF in Gas Turbine Blades**

Gas turbine blades operate under extreme conditions of high temperature and cyclic mechanical loads, making them susceptible to thermo-mechanical fatigue (TMF). Understanding TMF behavior in gas turbine blades is critical for improving their performance and durability. This case study examines the TMF behavior of gas turbine blades made from a nickel-based superalloy, highlighting the experimental procedures, computational modeling, and mitigation strategies employed to enhance blade life.

The gas turbine blades in this study are made from a nickel-based superalloy, renowned for its high-temperature strength, resistance to creep, and oxidation. The specific alloy used is IN738, widely utilized in aerospace and power generation applications. Standardized test specimens were machined from gas turbine blades to ensure uniformity. The specimens were polished to remove any surface imperfections that could act as stress concentrators.

TMF tests were conducted using specialized machines capable of applying cyclic thermal and mechanical loads. The specimens were subjected to temperature cycles ranging from 400°C to 900°C, with mechanical loads applied in both in-phase (IP) and out-of-phase (OP) conditions. The testing frequency was set to 1 Hz to replicate the operational conditions of gas turbines. Advanced microscopy techniques, including Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM), were used to analyze the microstructural changes in the specimens after TMF testing. Fractographic analysis was conducted to identify the mechanisms of crack initiation and propagation.

Finite Element Analysis (FEA) was performed to simulate the stress and temperature distributions in the turbine blades during operation. The model incorporated the cyclic thermal and mechanical loads applied during TMF testing. Crystal plasticity models were used to simulate the microstructural behavior of the nickel-based superalloy under TMF conditions. These models accounted for the slip and twinning mechanisms that contribute to fatigue damage. Damage mechanics models were integrated with FEA to predict the initiation and growth of fatigue cracks. These models used continuum damage mechanics (CDM) theories to describe the progressive degradation of material properties.

The TMF tests revealed distinct differences in fatigue behavior under IP and OP loading conditions. IP loading resulted in higher fatigue life compared to OP loading, due to the favorable alignment of thermal and mechanical stresses. Microstructural analysis showed that TMF damage was characterized by the formation of oxide scales, which acted as crack initiation sites. Cracks propagated along grain boundaries and through the gamma prime (γ′\gamma'γ′) precipitates. FEA simulations indicated that the highest stress concentrations occurred at the blade's leading and trailing edges, which corresponded with the experimental crack initiation sites. Crystal plasticity modeling provided insights into the slip and twinning mechanisms, revealing that dislocation motion was a primary contributor to fatigue damage. Damage mechanics modeling accurately predicted the crack growth patterns observed in the experiments.

Based on the findings, several mitigation strategies were proposed to enhance the TMF resistance of gas turbine blades. Developing new alloy compositions with improved microstructural stability and oxidation resistance, such as adding elements like rhenium and ruthenium to the alloy to enhance creep resistance and phase stability, was recommended. Applying thermal barrier coatings (TBCs) and oxidation-resistant coatings to protect the blade surface from high-temperature oxidation was suggested. These coatings act as a thermal insulator, reducing the surface temperature and mitigating oxidation damage. Optimizing the design of turbine blades to minimize stress concentrations, including redesigning blade geometries to distribute thermal and mechanical loads more evenly and incorporating cooling channels to manage temperature gradients, was also proposed. This case study demonstrates the importance of understanding TMF behavior in gas turbine blades made from nickel-based superalloys. Through a combination of experimental testing and computational modeling, critical insights into the mechanisms of TMF damage were obtained. The proposed mitigation strategies offer potential pathways to enhance the performance and longevity of gas turbine blades, contributing to improved efficiency and reliability of gas turbine engines.

## Conclusion

The analysis of thermo-mechanical fatigue (TMF) in high-temperature superalloys for gas turbine applications underscores the critical importance of understanding the complex interactions between thermal and mechanical loads that these materials endure. This study has demonstrated that high-temperature superalloys, particularly nickel-based alloys, possess excellent mechanical properties and resistance to creep, oxidation, and corrosion, making them suitable for extreme operational conditions. However, the cyclic nature of thermal and mechanical stresses necessitates a detailed investigation into TMF behavior to ensure the reliability and longevity of gas turbine components.

Experimental methods, including TMF testing, microstructural analysis, and fractography, have provided valuable insights into the mechanisms of crack initiation and propagation under cyclic loading conditions. The observed differences in fatigue life under in-phase and out-of-phase loading conditions highlight the significance of aligning thermal and mechanical stresses to enhance fatigue resistance. The use of advanced microscopy techniques has revealed that microstructural stability, oxidation resistance, and creep-fatigue interactions are pivotal in determining the TMF performance of high-temperature superalloys.

Computational modeling, encompassing finite element analysis (FEA), crystal plasticity modeling, and damage mechanics, has proven to be an indispensable tool in predicting the stress distribution, deformation behavior, and fatigue life of gas turbine components. These models, validated against experimental data, offer a comprehensive understanding of the material behavior at both macroscopic and microscopic levels. The integration of oxidation and corrosion modeling has further elucidated the synergistic effects of environmental degradation and mechanical loading on TMF resistance.

The proposed mitigation strategies, including material optimization, protective coatings, and component design enhancements, provide a roadmap for improving the TMF resistance of gas turbine blades. Developing new alloy compositions with enhanced microstructural stability, applying thermal barrier coatings to reduce surface temperatures, and optimizing blade geometries to minimize stress concentrations are crucial steps towards extending the service life of gas turbine components.

In conclusion, the combined approach of experimental investigation and computational modeling offers a robust framework for analyzing and mitigating TMF in high-temperature superalloys. Ongoing research and advancements in material science and engineering are essential to further enhance the performance and durability of gas turbine components, thereby contributing to the overall efficiency and reliability of gas turbine engines in aerospace and power generation applications.

## References

1. Reed RC. The superalloys: Fundamentals and applications. Cambridge University Press; c2006.
2. Gabb TP, Gayda J, Kantzos P. Effects of heat treatment on the thermo-mechanical fatigue of a superalloy disk material. NASA/TM-2002-211876; c2002.

3. Evans HE. Oxidation of high-temperature coatings. In: High temperature coatings. Elsevier; 2005. p. 149-89.
4. Rae CMF, Reed RC. Nickel-based superalloys. In: Physical metallurgy. Elsevier; c2007. p. 2189-235.
5. Pollock TM, Tin S. Nickel-based superalloys for advanced turbine engines: Chemistry, microstructure, and properties. J Propuls Power. 2006;22(2):361-74.
6. Matan N, Cox DC, Cox D, Carter P, Taylor MP. Creep of CMSX-4 superalloy single crystals: Effects of misorientation and temperature. Acta Mater. 1999;47(5):1517-32.
7. Pineau A, Antolovich SD. High temperature fatigue of nickel-base superalloys - A review with special emphasis on deformation modes and oxidation. Eng Fail Anal. 2009;16(8):2668-97.
8. MacKay RA, Davidson DL. Oxidation effects in high-temperature fatigue crack growth of a nickel-base superalloy. Metall Mater Trans A. 2007;38(8):1891-901.
9. Viswanathan R, Bakker W. Materials for ultra-supercritical fossil power plants. J Mater Eng Perform. 2001;10(1):81-95.
10. Suresh S. Fatigue of materials. Cambridge University Press; c1998.