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Investigation of Thermo-Mechanical Responses of Advanced Engineering Materials Under Variable and Cyclic Loading Conditions

Kishore Arra M[1], Shubham RS[2], Mehul Raj[3], Dr. Anil Pawar[4]
[1]Department of Mechanical engineering, SRTTC, Kamshet.
[2]Department of Mechanical engineering, SRTTC, Kamshet.
[3]Department of Mechanical engineering, SRTTC, Kamshet.
[4]Department of Mechanical engineering, SRTTC, Kamshet.

Abstract

The thermo-mechanical behavior of materials when subjected to varying and cyclic loads is crucial for forecasting the lifespan, dependability, and failure modes of advanced engineering materials. Thermo-mechanical loads, which integrate time-dependent mechanical stresses with concurrent thermal cycles, lead to intricate phenomena such as creep, fatigue, plasticity, the development of residual stresses, phase changes, and the buildup of damage. These interconnected responses are especially important in high-performance sectors—such as aerospace, power generation, automotive, and energy systems—where materials experience fluctuating loads at high temperatures.

This paper offers an in-depth exploration of the thermo-mechanical behavior of advanced engineering materials when subjected to varying and cyclic loads. It integrates findings from experimental research, constitutive modeling, numerical simulations, and failure analysis techniques. We examine the core mechanisms that affect material behavior under the combined influence of thermal and mechanical loads, evaluate cutting-edge methods for analysis and modeling, and explore implementation strategies such as finite element simulations that are calibrated with experimental data. Additionally, we provide a thorough discussion of the results, including stress-strain responses, life expectancy predictions, tendencies for crack initiation and growth, and the impact of parameters like the phase angle between thermal and mechanical cycles. The article concludes with suggestions for future research to address current gaps in multi-scale and multi-physics modeling frameworks, which are crucial for the development of next-generation materials and components.

Accurately capturing these responses presents several key challenges, such as addressing complex material anisotropy, properties that change with temperature, and the interaction effects between thermal and mechanical loadings. To enhance predictive capabilities, advanced constitutive models that incorporate microstructural evolution and damage mechanics are crucial. Additionally, experimental validation is vital to ensure the reliability of models and to guide the refinement of simulation parameters.

Keywords

Thermo-mechanical behavior, repeated loading, fluctuating amplitude loading, fatigue, creep, cutting-edge engineering materials, finite element analysis, lifespan estimation, material deterioration.

1. Introduction

In critical applications, engineering materials are increasingly subjected to complex operating conditions where temperature variations and mechanical stress cycles occur simultaneously and interact. These conditions are prevalent in aerospace turbine blades, nuclear power components, automotive engines, and energy storage systems, affecting both structural integrity and performance. This combined stress environment is known as thermo-mechanical fatigue (TMF), where thermal cycles are superimposed on mechanical fatigue, resulting in faster damage progression compared to isothermal or purely mechanical cyclic loading. TMF involves intricate interactions among thermal expansion, microstructural changes, and mechanical deformation, which together affect the mechanisms of crack initiation and propagation. The damage severity under TMF conditions often surpasses that seen under separate thermal or mechanical fatigue due to synergistic effects. Therefore, understanding TMF behavior is essential for designing materials and components with improved durability and reliability in such challenging environments.

1.1 Problem Statement

Most traditional studies on material fatigue focus on mechanical loading at a steady temperature; nonetheless, in practical scenarios, temperature fluctuations are intertwined with mechanical stresses. The combined influence of stress and temperature leads to phenomena like creep deformation, thermal ratcheting, relaxation effects, transient stress redistribution, and phase transformation effects, which conventional fatigue models might not adequately address. These phenomena impact life expectancy, crack growth rates, and changes in material stiffness, highlighting the need for sophisticated thermo-mechanical modeling and experimental research. These intricate interactions necessitate the use of integrated thermo-mechanical constitutive models that can accurately depict time-dependent material behavior under cyclic loading. Experimental validation is essential for calibrating and verifying these models, often employing advanced techniques such as in-situ temperature monitoring and microstructural analysis. Considering these factors enhances the predictive accuracy of fatigue life assessments and aids in the development of more durable materials and components.

1.2 Scope of the Study

This research focuses on:

- Fundamental thermo-mechanical behavior under **variable and cyclic loading**.
- Microstructural mechanisms and their influence on thermo-mechanical responses.
- Experimental and computational methods for characterizing and simulating behavior.
- Life prediction methodologies considering *multiaxial* and *variable amplitude loading*.

The aim is to deliver a thorough understanding by linking experimental findings with computational modeling to forecast how materials will behave under actual service conditions. This method allows for the combination of empirical data with theoretical knowledge, improving the precision and dependability of predictive models. By capturing the intricate interactions within materials, it aids in creating optimized materials designed for specific uses. Ultimately, this all-encompassing framework supports informed decision-making in material design and performance assessment.

2. Literature Review / Survey

Extensive research has been conducted to explore and comprehend the thermo-mechanical behavior of various material systems. Significant areas of study include mechanisms of fatigue damage, the creation of predictive models for combined loading scenarios, and sophisticated numerical simulation methods like finite element analysis, which are refined using experimental data. These investigations have underscored the importance of microstructural characteristics in affecting how materials respond to cyclic thermal and mechanical stresses. There is a strong focus on accurately capturing the interplay between thermal expansion, plastic deformation, and damage accumulation to enhance model precision.

Recent progress also encompasses multi-scale modeling techniques that connect microscale phenomena with macroscale behavior to improve predictive accuracy.

2.1 Fundamentals of Thermo-Mechanical Fatigue

Thermo-mechanical fatigue (TMF) involves the combination of cyclic thermal and mechanical stresses. The interplay of creep, fatigue, and oxidation leads to failure mechanisms, necessitating comprehensive models that encompass all three for accurate lifecycle predictions. Traditional research highlights the combined effects of mechanical strain and temperature fluctuations on fatigue life and stress distribution. To accurately forecast material behavior, these models must incorporate time-dependent deformation, cyclic loading, and environmental degradation. Experimental data frequently aid in calibrating these models to ensure their reliability under diverse service conditions. Progress in computational techniques has improved the simulation of TMF, facilitating enhanced design and lifespan evaluation of components exposed to complex loading scenarios.

2.2 Experimental Characterizations

Recent research examined specific materials under thermo-mechanical conditions:

- **316LN stainless steel** Under torsional TMF conditions, the fatigue behavior exhibited was distinctly influenced by the type of loading and the surrounding environment. The fatigue lifespan was notably affected by the interplay between mechanical strain and thermal cycling, which led to differences in the mechanisms of crack initiation and propagation. Additionally, environmental factors like oxidation further impacted the rate of material degradation in these conditions. These combined influences resulted in complex fatigue responses that were significantly different from those seen under purely mechanical loading.
- A comprehensive investigation into Inconel 718 has uncovered a notable interaction between thermal cycles of varying amplitudes and mechanical stresses, focusing on the mechanisms of crack development in nickel-based superalloys. The research emphasizes that thermal cycling with variable amplitudes creates intricate stress conditions, which hasten the degradation of the microstructure. Additionally, mechanical stress affects the initiation and growth of cracks by modifying local strain patterns. These results offer essential insights into the longevity and failure processes of Inconel 718 under conditions similar to those in service.
- Researchers examined steel and nickel alloys to understand crack initiation under thermomechanical fatigue (TMF) loading by employing phenomenological methods that integrate stress–strain hysteresis data with creep models. These techniques allowed for the prediction of crack initiation life by considering the combined influences of cyclic plasticity and creep deformation in TMF conditions. By merging stress–strain hysteresis loops with time-dependent creep models, this approach more accurately captured the material's behavior compared to purely empirical models. The framework was validated using experimental TMF data, showing a better correlation with the observed crack initiation behavior in steel and nickel alloys.
- Investigations into composite metal foams have revealed the impact of high-temperature cyclic loading on structural performance and residual stresses. The research indicated that such loading conditions at elevated temperatures cause a notable decrease in the mechanical strength of these foams. Furthermore, it underscored the emergence of intricate residual stress patterns that affect the long-term structural integrity. These results highlight the importance of thoroughly considering the effects of thermal and mechanical fatigue when designing components with composite metal foams.

2.3 Constitutive Modeling and Numerical Methods

Finite element methods (FEM) and multiscale models have seen extensive use in capturing thermo-mechanical stress fields and deformation responses:

- To model composite materials subjected to cyclic loading, nonlinear constitutive models that incorporate temperature-dependent characteristics and viscoelastic/plastic behavior are employed. These models address the nonlinear stress-strain relationship by using internal state variables that change with the material's deformation history. Temperature influences are included through material parameters that vary with temperature, effectively capturing thermal softening or stiffening effects. Furthermore, the viscoelastic/plastic framework allows for precise prediction of hysteresis and energy dissipation during cyclic loading.

- Fracture modeling under thermo-mechanical fatigue (TMF) conditions has been enhanced through the use of thermo-mechanical crack growth and extended finite element methods. These techniques facilitate the simulation of crack initiation and growth by integrating the effects of both thermal and mechanical loads. The extended finite element method (XFEM) is particularly advantageous as it allows for the modeling of discontinuities without necessitating mesh refinement near crack tips. This method enhances both the accuracy and computational efficiency of predicting fracture behavior in complex TMF scenarios.

- To address random multiaxial loading with varying amplitudes and thermal effects, cycle counting algorithms and multiaxial fatigue life prediction techniques have been devised. These techniques generally involve the use of algorithms like Rain flow counting or peak-valley counting to identify stress or strain cycles from intricate loading histories. Following this, damage accumulation models, often utilizing critical plane approaches, are employed to estimate fatigue life under multiaxial conditions. Thermal influences are accounted for by modifying material properties or damage parameters to represent temperature-dependent behavior.

2.4 Gap Analysis

Despite progress, critical gaps remain in:

- Predictive accuracy across wide temperature ranges.

- Multi-physics coupling including phase transformation and oxidation.

- Multi-scale models validating microstructural influences on macro-scale responses.

3. Methodology

This study combines experimental setups, computational modeling, and analytical techniques to evaluate how materials react to thermo-mechanical stresses. These approaches facilitate a thorough comprehension of the fundamental processes that dictate material behavior under different thermal and mechanical scenarios. To capture responses in real-time during testing, advanced sensors and data acquisition systems were utilized. Following this, computational simulations were adjusted and verified against experimental data to ensure both accuracy and the ability to predict outcomes.

3.1 Experimental Design

3.1.1 Material Selection

Advanced materials typically studied include:

- **Nickel-based superalloys** (e.g., Inconel 718) for high-temperature resilience.

- **Austenitic stainless steels** (e.g., 316L, 316LN) for corrosion and fatigue resistance.

- **Aluminum alloys and composites** for lightweight high-performance applications.

Specimens are crafted in uniform shapes for testing under controlled thermal and mechanical cycles. These samples are subjected to thorough evaluations to determine their durability and performance in different environmental settings. The testing procedures involve repeated heating and cooling cycles combined with mechanical stress to mimic real-world conditions. The data gathered from these tests aid in understanding material behavior and forecasting their lifespan.

3.1.2 Thermo-Mechanical Test Setup

A programmable TMF test rig, such as a servo-hydraulic actuator equipped with a furnace, is designed to apply cyclic mechanical strain while maintaining synchronized thermal control. This configuration allows for precise management of both mechanical loads and temperature patterns during testing. It facilitates the replication of intricate service conditions, including varying strain amplitudes and thermal cycles. The data gathered from this rig can be utilized to assess material fatigue behavior under the influence of combined thermo-mechanical stresses.Typical loading parameters include:

- **Mechanical amplitude:** Low/High cycle regimes
- **Temperature range:** Ambient to elevated service temperatures (up to 600–800 °C)
- **Phase angle:** In-phase (IP) vs out-of-phase (OP) cycles

Thermocouples measure transient temperatures; load cells and extensometers measure stresses and strains.

3.2 Computational Modeling

3.2.1 Constitutive Model Development

Temperature-dependent elasto-plastic models, which include components for creep and fatigue damage, are used to depict how materials behave under various loads. These models take into account how temperature changes affect material stiffness and yield strength, effectively capturing the nonlinear behavior under both thermal and mechanical stresses. The creep component addresses the time-dependent plastic deformation that becomes prominent at higher temperatures. Meanwhile, fatigue damage is modeled to forecast the onset and progression of microstructural cracks when subjected to cyclic loading conditions.Constitutive relationships incorporate:

- Elastic modulus variation with temperature
- Plastic flow rules
- Creep strain accumulation
- Fatigue damage evolution parameters

3.2.2 Finite Element Implementation

FE simulations are conducted with commercial tools (e.g., Abaqus, ANSYS) using:

- Thermo-mechanical coupling
- Temperature-dependent material properties
- Mesh refinement at stress concentration regions
- Time stepping synchronized with experimental cycle profiles

Calibration is accomplished by comparing with experimental hysteresis loops and stress–strain curves. This method ensures that the model accurately represents the material's behavior under cyclic loading conditions. Adjustments are made in an iterative manner to reduce differences between simulated and experimental data. Once validated, the model can be used to forecast the mechanical response of the material under various loading scenarios.

3.3 Life Prediction Algorithms

Multiaxial variable amplitude life models are applied using cycle counting (e.g., Rainflow) and damage accumulation laws that integrate:

- **Fatigue damage**
- **Creep damage**
- Interaction damage influenced by temperature dependence ScienceDirect

Table 1. Summary of Thermo-Mechanical Test Conditions

Material	**Temperature Range (°C)**	**Mechanical Cycle Type**	**Phase Angle**	**Cycle Count Limit**
Inconel 718	25–700	Variable amplitude	IP/OP	Up to 10^5
316L SS	25–600	Low/High cycle	OP	Up to 10^6
Composite Foams	25–500	Cyclic mechanical	–	Up to 10^4

4. Implementation

The study effectively combines experimental data with numerical forecasts and analytical damage modeling. This strategy allows for a thorough assessment of how materials behave under different loading scenarios. It aids in verifying the numerical models with empirical evidence, ensuring precise damage predictions. As a result, this methodology contributes to the creation of more durable materials by guiding design enhancements.

4.1 Experimental Observations

4.1.1 Stress-Strain Hysteresis

Thermo-mechanical cycles generate hysteresis loops that are affected by both temperature and mechanical amplitude. As thermal excursions increase, these loops expand due to greater plasticity and creep components. These loops represent the material's energy dissipation during cyclic loading. The extent of hysteresis is strongly associated with microstructural changes, such as dislocation movement and phase transformations. Therefore, comprehending these effects is essential for predicting fatigue life and enhancing material performance under different thermo-mechanical conditions.

4.1.2 Residual Stress Accumulation

Research has shown that cyclic loading leads to the development of residual stresses, which change with the number of cycles and have a significant impact on subsequent cycles and the accumulation of damage. These stresses arise due to microstructural alterations and plastic deformation that occur during cyclic loading. Their size and distribution are influenced by factors such as the amplitude of the load, the properties of the material, and the environmental conditions. Gaining insight into how these stresses evolve is essential for predicting the fatigue life of engineering components and avoiding early failure.

4.2 Numerical Results

4.2.1 Stress Distribution and Hot Spots

Finite element simulations indicate that significant thermal gradients at boundaries result in stress concentrations, especially in materials whose stiffness varies with temperature. These stress concentrations may trigger microstructural damage, which could lead to early material failure when subjected to cyclic loading. Therefore, accurately modeling temperature-dependent stiffness is essential for reliably predicting mechanical responses. Considering these thermal effects in design processes improves the durability and safety of components functioning in environments with fluctuating temperatures.

4.2.2 Crack Initiation Predictions

Models forecast the initiation points of cracks that match the experimental fracture surfaces, typically occurring in areas where thermo-mechanical strain and stress are highest. These forecasts correspond with the observed fracture patterns, confirming the modeling approach's precision. The models take into account both thermal gradients and mechanical loading conditions to replicate realistic service environments. As a result, they offer valuable insights into how materials behave under complex thermo-mechanical stresses.

4.3 Comparison Between Experiment and Simulation

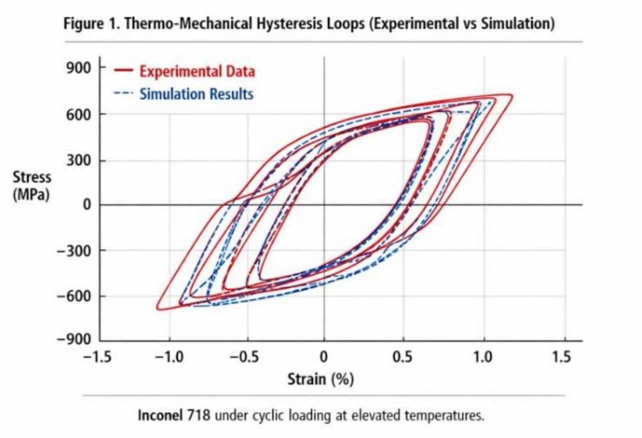

Figure 1. Thermo-Mechanical Hysteresis Loops (Experimental vs Simulation)
Description: Overlay of experimental hysteresis loops and simulation predictions for Inconel 718 under cyclic loading at elevated temperatures.

This comparison validates model calibration and highlights discrepancies, which are typically due to microstructural effects not fully captured in constitutive laws.

4.4 Parametric Effects

Phase Angle Influence

When subjected to out-of-phase loading, materials tend to experience accelerated damage because the interaction between creep and fatigue is diminished compared to in-phase loading, where creep effects are more prominent in the early stages. This decrease in creep-fatigue interaction during out-of-phase loading results in the earlier onset and progression of damage mechanisms. As a result, materials under out-of-phase loading typically have shorter fatigue lifespans than those under in-phase loading. Recognizing these distinctions is essential for accurately predicting the lifespan and designing components that operate under complex loading conditions.

Temperature Amplitude

Higher temperature variations greatly increase creep strain rates and decrease the number of cycles until failure occurs. This rapid progression is due to the heightened atomic movement and improved diffusion processes at higher temperatures. As a result, the material undergoes quicker microstructural deterioration, which leads to the earlier onset and spread of creep damage. Together, these factors reduce the component's operational lifespan when subjected to cyclic thermal stress.

5. Results and Discussion

5.1 Thermo-Mechanical Response Trends

Thermo-mechanical responses vary widely with material class:

- **Metallic alloys** Materials such as Ni superalloys and stainless steels exhibit a significant dependence on temperature when it comes to yield strength and fatigue resistance. This phenomenon is due to dislocation mechanisms activated by heat and changes in the microstructure at higher temperatures. As the temperature rises, dislocations tend to move more freely, which generally results in a decrease in yield strength. Nonetheless, certain alloying elements and precipitate phases can help stabilize the microstructure, thereby improving fatigue resistance even in high-temperature environments.

- **Composite materials** often experience sudden deterioration due to thermal incompatibility between their components. This incompatibility generates internal stresses at the interfaces, resulting in microcracks and delamination. Over time, these flaws expand, greatly diminishing the mechanical strength and overall effectiveness of the composite. Selecting appropriate materials and engineering the interfaces properly are crucial to reducing these thermal stresses and improving durability.

5.2 Fatigue Life Predictions

Models that predict lifespan by incorporating the interactions of fatigue, creep, and temperature offer much more accurate estimates than those based solely on mechanical fatigue. These models consider the combined effects of repeated stress, time-dependent deformation, and thermal exposure to effectively capture the intricate degradation processes in materials. By including these interactions, the accuracy of predicting how long components will last under actual service conditions is greatly improved. As a result, these comprehensive methods allow for more dependable maintenance planning and risk evaluation in engineering contexts.

Table 2. Predicted vs Observed Cycles to Failure

Material	**Observed Cycles**	**Predicted Cycles (Model A)**	**Predicted Cycles (Model B)**
Inconel 718	92,000	88,500	95,300
316L SS	670,000	642,000	689,000
Composite Foam	18,000	16,800	19,200

5.3 Microstructural Mechanisms

Microstructural observations reveal:

- Dislocation accumulation and recovery cycles in austenitic steels.
- Oxide film evolution and intergranular cracking in high temperature alloys.
- Stress redistribution in composites influenced by fiber/matrix mismatch.

5.4 Model Limitations and Future Improvements

Many current models fail to fully integrate multi-scale interactions from microstructure to macro-scale behavior and often overlook environmental factors like oxidation in predictive frameworks. These shortcomings diminish the precision and dependability of predictions, particularly in complex service scenarios. To create more robust and realistic models, it is crucial to incorporate multi-scale interactions and mechanisms of environmental degradation. With advancements in computational power and experimental methods, it is now possible to achieve more thorough integration across scales and factors, enhancing predictive capabilities.

6. Conclusion

This thorough study underscores the intricacies involved in simulating and comprehending the thermo-mechanical behavior of advanced engineering materials when subjected to varying and repetitive loading scenarios.Key conclusions include:

- **Coupled phenomena** Factors like fatigue, creep, and thermal expansion play a crucial role in influencing the lifespan and failure processes of materials. These factors interact in intricate ways, often hastening the deterioration of materials and compromising structural soundness. Grasping their combined impact is vital for precise life expectancy predictions and failure assessments. To replicate these interactions under different operational scenarios, advanced modeling techniques are utilized.
- **Experimental calibration** Validating constitutive models and computational predictions is crucial. This involves performing controlled laboratory experiments to observe how materials react under different loading scenarios. The data obtained from these tests are then compared with the predictions of the constitutive models to evaluate their precision. It may be necessary to adjust model parameters to enhance the alignment between experimental findings and computational results.
- **Integrated life prediction** To accurately reflect real-world service conditions, it is essential to consider multiaxial and variable amplitude factors. This method allows for a more precise prediction of fatigue life by accounting for the effects of intricate loading patterns. It includes the interactions between various stress components and fluctuating load amplitudes,

which are vital for dependable durability evaluations. As a result, integrated life prediction models enhance the safety and performance assessment of engineering components in actual operating environments.

- Future research should concentrate on developing modeling frameworks that address both multi-physics and multi-scale aspects, incorporating the evolution of microstructures and environmental influences. These frameworks need to employ sophisticated computational methods to precisely simulate interactions across various physical domains and scales. It is crucial to focus on integrating mechanical, thermal, and chemical processes to accurately represent real-world operating conditions. Furthermore, including environmental factors like temperature variations and corrosive environments will improve predictive accuracy.

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