A High-Temperature Sliding Contact Fatigue Life Prediction Model Based on Surface Integrity

Beibei Liu*

Xi' AN MINGDE INSTITUTE OF TECHNOLOGY, Xi' an, 710124, China
Corresponding author: 18502973340@163.com

Abstract: *The fatigue failure of mechanical components under high-temperature sliding contact conditions is a key bottleneck issue in major equipment fields such as aero-engines and advanced gas turbines. Traditional life prediction models often treat the material as a homogeneous body and fail to fully account for the decisive influence of the surface integrity state, which is shaped jointly by the manufacturing and service processes, on the fatigue behavior, thereby leading to significant dispersion in the prediction results. To address this problem, this paper aims to construct a physics-mechanism-driven life prediction model that integrates multi-dimensional characterization parameters of surface integrity. The study systematically presents the characterization methods of surface topography, residual stress, and microstructure, as well as their evolution laws under high-temperature sliding contact. It deeply reveals the multi-mode damage competition mechanism under thermo-mechanical coupling and creep-fatigue interaction. Based on the multi-scale damage coupling theory, this work establishes a theoretical framework that quantitatively integrates key surface integrity parameters into the damage evolution equation and develops a numerical solution algorithm coupling finite element and damage mechanics. This model achieves a full-process physical simulation from the initial surface integrity state to final failure, providing a more accurate theoretical tool for the anti-fatigue design and reliability assessment of high-temperature sliding contact components.*

Keywords: *Surface Integrity, High-Temperature Sliding Contact, Fatigue Life Prediction, Damage Mechanism, Multi-Scale Modeling, Thermo-Mechanical Coupling*

Introduction

Under high-temperature sliding contact service conditions, the fatigue life of mechanical components is profoundly influenced by the surface integrity state defined jointly by the manufacturing process and the initial service load. As a comprehensive concept covering surface topography, residual stress layer, and microstructural gradient, surface integrity directly dominates the initiation location, propagation path, and rate of fatigue cracks. However, existing studies mostly focus on a single factor or on room-temperature conditions, and they lack a systematic description of the multi-parameter coupled evolution of surface integrity under high-temperature environments and its interaction with complex damage mechanisms. This limitation renders the traditional life prediction models based on stress or strain methods of limited applicability in high-temperature contact fatigue scenarios. Therefore, developing a physically predictive model that can deeply integrate the multi-dimensional and time-varying characteristics of surface integrity and rigorously account for the unique thermo-mechanical coupling and time-dependent damage mechanisms inherent to high-temperature environments is not only of significant scientific value for deepening the fundamental understanding of fatigue theory but also of urgent engineering necessity for achieving precise life design and reliability enhancement of key components in high-parameter equipment. The present study is carried out around this core objective.

1. Surface Integrity Characterization and Its Influence Mechanism on Fatigue Behavior

1.1 Characterization Parameters of Surface Topography Features under High-Temperature Sliding Contact

The high-temperature sliding contact process significantly alters the material surface topography, and the accurate characterization of its characteristic parameters serves as the foundation for evaluating surface integrity. The key characterization parameters include three-dimensional surface roughness, the arithmetic mean deviation of the profile, the maximum height of the profile, and the directionality of the surface texture. Under high-temperature environments, the coupling effects of plastic deformation, material transfer, and oxidative wear on the contact surface lead to the insufficient characterization capability of traditional two-dimensional roughness parameters. Therefore, the introduction of scale-dependent parameters based on fractal theory and the bearing area curve analysis can more effectively quantify the distribution and evolution of surface asperities under thermal-mechanical loads. These topographic features directly influence the local concentration degree of the contact stress field, the retention capability of the lubricating medium, and the initiation location of microcracks, making them indispensable input variables for constructing the initial conditions of fatigue damage. To accurately capture the dynamic changes under high-temperature conditions, it is necessary to combine in-situ measurement techniques with non-contact three-dimensional optical profilometers to obtain real-time topographic evolution data during the wear process. The ultimate goal of characterization is to establish a quantitative relationship between the topographic parameters and the local stress concentration factor, thereby providing accurate geometric boundary conditions and damage initialization basis for subsequent multi-scale modeling[1].

1.2 The Formation and Evolution Law of the Residual Stress State in the Surface Layer

The residual stress state in the surface layer is an internal stress equilibrium system formed by the combined action of non-uniform plastic deformation, thermal gradients, and phase transformation during the high-temperature sliding contact process. Its formation originates from the plastic strain gradient caused by mechanical loading and the thermal strain mismatch resulting from the difference in thermal expansion coefficients induced by high temperature. Under cyclic sliding contact, the residual stress is not static, and its evolution law is comprehensively influenced by the load level, sliding speed, ambient temperature, and number of cycles. The initial residual compressive stress may delay the initiation of fatigue cracks, but under the repeated action of thermo-mechanical coupling loads, stress relaxation and redistribution may lead to the sign reversal or amplitude attenuation of the stress field. To accurately describe this dynamic evolution process, it is necessary to incorporate the constitutive model and the cyclic softening/hardening behavior, which has a decisive influence on the prediction accuracy of fatigue life.

1.3 Correlation Analysis between the Microstructure State and Surface Integrity

Surface integrity not only covers the geometric and mechanical states but also extends to the microstructure state of the material subsurface layer. The microstructure evolution of the surface layer induced by high-temperature sliding contact includes grain refinement or coarsening, dislocation structure reorganization, second-phase precipitation or dissolution, and possible dynamic recrystallization. These evolutions directly alter the local mechanical properties of the material, such as hardness, yield strength, and fracture toughness. A strong coupling relationship exists between the gradient change of the subsurface microstructure and the residual stress field as well as the depth of the plastic deformation layer. For example, a severely plastic deformed layer is usually accompanied by a high dislocation density and a compressive stress field, while high temperature may cause recrystallization softening of the surface layer, thereby weakening the material's ability to resist crack propagation. Therefore, conducting quantitative correlation analysis by taking the microstructure state as a core dimension of surface integrity is a necessary approach to revealing the deep-seated mechanism of high-temperature contact fatigue.

2. Fatigue Damage Mechanisms of High-Temperature Sliding Contact

2.1 Temperature-Dependent Mechanical Properties and Surface Response Characteristics of Materials

2.1.1 Temperature-Dependent Constitutive Behavior and Cyclic Softening/Hardening Mechanisms

The constitutive behavior of materials at high temperatures exhibits strong temperature dependence and rate sensitivity. Its constitutive model needs to incorporate viscoplastic mechanisms to describe the dislocation motion and diffusion creep behavior controlled by thermal activation. Under cyclic sliding contact loading, the subsurface material may induce cyclic softening or hardening due to the non-proportional cyclic loading path. This cyclic response characteristic is closely related to dynamic strain aging, dislocation cell structure evolution, and the interaction with second-phase particles, and it directly determines the rate and distribution of plastic strain accumulation, serving as the core material parameter for predicting damage initiation.

2.1.2 Time-Temperature Equivalence Effect and Creep-Fatigue Interaction

The high-temperature environment extends the time scale of load application, allowing the creep mechanism to intervene in the fatigue process. The creep-fatigue interaction manifests as time-dependent damage accumulation and stress relaxation. The time-temperature equivalence principle can provide an analytical framework in this context, but the locally instantaneous high temperature and high stress gradient induced by sliding contact render the classical steady-state creep model inapplicable. It is necessary to develop a constitutive relationship that can describe transient creep and its coupling with cyclic plasticity to quantify the additional damage contributed by creep voids or grain boundary sliding, which is a key feature distinguishing high-temperature contact fatigue from room-temperature fatigue[2].

2.1.3 Environmental Media Interaction and Surface Degradation Mechanisms

High-temperature operating conditions are often accompanied by oxidation or specific environmental media. The environmental interaction is not limited to the formation and rupture of surface oxide films but also involves the diffusion and penetration of oxygen along grain boundaries or defects, leading to the bulk degradation of the material's intrinsic mechanical properties. This environmentally assisted crack initiation mechanism transforms the surface response from a purely mechanical failure into a mechanical-chemical synergistic process. Characterizing the detrimental effects of environmental media on the ductility, fracture toughness, and recrystallization temperature of the material surface layer is a necessary component for completely defining the surface response characteristics.

2.2 Thermo-Mechanical Coupling and Stress Field Analysis during the Sliding Contact Process

2.2.1 Frictional Heat Source Model and Unsteady Temperature Field Calculation

The frictional energy dissipation at the sliding contact interface constitutes a moving heat source. Its accurate modeling requires consideration of the dynamic changes in the friction coefficient with temperature, velocity, and surface state. Based on the heat conduction theory and combined with the temperature dependence of the material’s thermophysical properties, the unsteady temperature field in the contact zone and the subsurface layer can be obtained through calculation. The calculation results show that this temperature field exhibits extremely high spatial gradients and temporal fluctuations, and its peak temperature can approach or even exceed the material’s phase transition point, exerting a decisive influence on the local material state.

2.2.2 Coupling Analysis of Thermoelastic Stress and Thermoplastic Stress

The thermal expansion constraint induced by the non-uniform temperature field generates thermoelastic stress. When the local stress exceeds the high-temperature yield limit, irreversible thermoplastic deformation occurs, and a new residual stress field is subsequently produced. The key to thermo-mechanical coupling analysis lies in solving the elastic-plastic stress-strain field under the combined action of mechanical load and thermal load. The finite element analysis combined with the incremental iteration method is the primary approach, which requires consideration of the temperature nonlinearity of material properties and the deformation history to reveal the evolution law of the stress field amplitude, distribution, and mean stress under cyclic loading.

2.2.3 Stress State Evolution and Determination of Potential Damage Locations

One of the core objectives of thermo-mechanical coupling analysis is to determine the locations of the maximum equivalent stress, the maximum shear stress, and the maximum hydrostatic tensile stress, as well as their evolution paths. Under high-temperature sliding contact, the position of the maximum shear stress may migrate from the subsurface layer to a greater depth due to the thermal softening effect of the material. The hydrostatic tensile stress component is crucial for creep damage and the propagation of cracks in the opening mode. By analyzing the multiaxiality and non-proportionality of the stress state, one can accurately determine the critical location where fatigue damage is most likely to initiate and the dominant stress mode[3].

2.3 Fatigue Crack Initiation and Propagation Paths Based on Surface Integrity

2.3.1 Competitive Mechanism of Multi-Mode Crack Initiation

Crack initiation does not follow a single mechanism but rather results from the competition between surface integrity parameters and the local stress state. Transgranular initiation may occur at stress concentrations induced by surface roughness; intergranular initiation may occur in the surface residual tensile stress zone or in regions with microstructural weakening (such as coarse grain boundaries or precipitate bands); and at the subsurface location of the maximum shear stress amplitude, crack initiation may arise from extrusions and intrusions formed by dislocation accumulation. The dominant initiation mode depends on the ratio of the local driving force to the material resistance at each location, which constitutes a multi-site competitive damage initiation problem.

2.3.2 Short-Range Barrier Effect of Microstructure on Short Crack Propagation

The early propagation of cracks after initiation (the short crack stage) is strongly influenced by microstructural details and exhibits significant discontinuity and scatter. Grain boundaries, phase boundaries, and second-phase particles all constitute short-range barriers, and the crack growth rate at this stage is highly sensitive to the local microstructure. The microstructural gradient defined by surface integrity, such as the plastically deformed layer, the recrystallized layer, and the oxidation-affected layer, provides a continuously changing micro-environment and resistance for short crack propagation. Understanding the propagation behavior of short cracks in a gradient microstructure is a key link connecting crack initiation and long crack propagation.

2.3.3 Main Crack Path Selection and Multi-Crack Interaction Model

After a short crack develops into a macroscopic main crack, its propagation path is jointly determined by the near-field stress intensity factor and the anisotropy of the material's fracture resistance. Under the complex stress field generated by high-temperature sliding contact, the crack may propagate along the direction of the maximum energy release rate, or it may deflect due to the influence of material texture or the residual stress field. Meanwhile, the interaction after the initiation of multiple cracks (such as stress field shielding or coalescence) will significantly affect the final life. Establishing a propagation model that considers the initial conditions of surface integrity, the evolution of the stress state, and multi-crack interactions is the ultimate theoretical challenge for achieving accurate life prediction.

3. Construction of a Fatigue Life Prediction Model Considering Surface Integrity

3.1 Theoretical Basis of Multi-Scale Damage Coupling

3.1.1 Macroscopic Continuum Framework and Phenomenological Damage Mechanics Characterization

Within the macroscopic continuum mechanics framework, fatigue damage is regarded as an internal variable, and its evolution is driven by a constitutive equation incorporating thermo-mechanical coupling effects. Based on the principles of irreversible thermodynamics, one can construct a free energy potential function that couples elasticity-plasticity, creep, and damage. The damage variable is associated with the degradation of the material's effective load-bearing area, and its evolution equation is driven by the accumulated plastic strain, hydrostatic stress, and temperature as driving potentials, thereby quantifying, at the macroscopic scale, the continuous degradation process of the material's load-bearing capacity caused by the deterioration of surface integrity.

3.1.2 Unified Evolution Criterion for Damage Mechanisms at the Mesoscopic Scale

To bridge the macroscopic response and the microscopic mechanisms, one needs to establish a unified evolution criterion for damage mechanisms at the mesoscopic scale. This criterion treats crack initiation and early propagation as the result of competition among the local stress-strain field, microstructural resistance, and environmental factors. By introducing a multiaxial fatigue parameter based on the critical plane method and combining it with a microstructural short-range barrier model, one can construct a physical mechanism framework capable of describing the evolution from dislocation accumulation to microvoid formation and then to microcrack coalescence, thereby providing a mesoscopic physical interpretation for the macroscopic damage variable[4].

3.1.3 Cross-Scale Correlation and Information Transfer Method

The core of achieving multi-scale coupling lies in establishing an effective method for cross-scale information transfer. This method adopts the representative volume element concept and transfers the average damage evolution rate and the constitutive softening effect calculated at the mesoscopic scale to the macroscopic scale through a homogenization method. Conversely, the non-uniform stress-strain field provided by the macroscopic scale serves as the boundary condition for the mesoscopic analysis. This top-down and bottom-up bidirectional coupling ensures that the gradient characteristics of surface integrity (such as the residual stress field and the microstructure gradient) can be coherently represented in the models at different scales.

3.2 Quantification of Key Surface Integrity Parameters and Model Integration

3.2.1 Dimensionality Reduction of Characterization Parameters and Extraction of Feature Vectors

The raw surface integrity data (such as three-dimensional topography point clouds, residual stress depth profiles, and EBSD orientation maps) are high-dimensional and massive, requiring feature extraction and dimensionality reduction. By applying methods such as principal component analysis, wavelet transform, or fractal dimension calculation, one can condense the complex surface state information into a limited set of feature parameter vectors with clear physical significance. This vector comprehensively characterizes the statistical features of the surface topography, the gradient features of the stress field, and the topological features of the microstructure, thus constituting the key input set of the model[5].

3.2.2 Coupling Modeling between the Parameters and the Damage Evolution Law

The extracted feature parameters of surface integrity are systematically integrated into the damage evolution equation. For example, one associates the amplitude and distribution parameters of surface roughness with the crack initiation driving force term; one introduces the principal components of the residual stress tensor as a mean stress correction term into the fatigue life equation; and one correlates the microstructural parameters such as grain size and dislocation density with the material cyclic hardening/softening law and the crack propagation resistance. By introducing weight coefficients and interaction terms, one can construct a parameterized coupling relationship matrix to quantify the contribution weight of each surface integrity element to the different stages of damage (initiation, short crack, and long crack).

3.2.3 Parameter Sensitivity Analysis and Model Order Reduction Based on Machine Learning

Facing the complex model with multiple parameters and nonlinear coupling, one adopts surrogate model technology based on machine learning to perform global sensitivity analysis. One constructs the sample space through Latin hypercube sampling, and one uses Gaussian process regression or deep neural networks to establish a high-precision mapping relationship from the surface integrity input parameters to the fatigue life output. Based on this, one can identify the key parameter combination that is most sensitive to life prediction, achieve model order reduction, and point out the critical optimization direction for process control, thereby improving the engineering practicality of the model.

3.3 Life Prediction Algorithm Framework and Model Validation Methods

3.3.1 Numerical Solution Framework Coupling Finite Element and Damage Mechanics

This work constructs an integrated numerical solution framework, the core of which is the user material subroutine interface of commercial finite element software (such as ABAQUS or ANSYS). In this framework, the finite element method is responsible for solving the macroscopic thermo-mechanical coupling field at each load increment step. The user-defined material subroutine then embeds the multi-scale damage coupling constitutive model and updates the material state (stress, strain, and damage) according to the current field variables. An implicit integration algorithm is adopted to ensure computational stability, and the cyclic iteration proceeds until the damage reaches a critical value, thereby realizing the numerical simulation of the entire life process of the component.

3.3.2 Hierarchical Strategy for Model Validation and Uncertainty Quantification

The model validation adopts a hierarchical strategy. First, at the material point level, this work validates the capability of the constitutive model to simulate uniaxial tension-compression, creep, and fatigue tests. Second, at the component level, this work compares the predicted and experimental crack initiation locations, propagation paths, and total life by simulating sliding contact fatigue tests on simplified specimens with a well-defined surface integrity state. To evaluate the prediction reliability, this work introduces an uncertainty quantification analysis and adopts the Monte Carlo method to account for the statistical scatter of surface integrity parameters, material properties, and loading conditions, thereby providing a prediction interval for the life rather than a single value[6].

3.3.3 Adaptability Assessment and Generalization Capability Discussion of the Prediction Model

The final model needs to be evaluated for its adaptability to different material systems, process conditions, and service environments. By applying the validated model to predict fatigue lives under unseen datasets (such as those from different surface treatment processes or slightly varied temperature conditions), one can test its generalization capability. This work discusses the main sources of prediction deviation, whether they arise from an insufficient description of a certain damage mechanism or from an inadequate characterization of the surface integrity parameters, thereby providing a clear technical route for the continuous iteration and improvement of the model.

Conclusion

This paper systematically investigates the influence mechanism of surface integrity on the high-temperature sliding contact fatigue behavior and constructs a life prediction model based on multi-scale damage physics. This study clarifies that the quantitative characterization methods of surface topography, residual stress field, and gradient microstructure are prerequisites for constructing a high-fidelity model. This research reveals that, under thermo-mechanical coupling and creep-fatigue interaction, there exist multiple modes of damage initiation and propagation determined by the competition between the surface integrity state and the local stress field. The established prediction model systematically integrates the characteristic parameters of surface integrity into the cross-scale damage evolution law and adopts a numerical solution framework coupled with the finite element method, thereby achieving a physical mechanism simulation of fatigue life and the quantification of the prediction interval. This model overcomes the deficiency of traditional empirical methods that insufficiently consider the surface state. Future research directions should focus on developing higher-fidelity cross-scale computational schemes to capture the dynamic evolution of the microstructure, extending the model's applicability to more complex multiaxial non-proportional loading and extreme environments, and exploring an inverse optimization design method for surface integrity process parameters based on this model, thus forming a closed-loop design theoretical system from manufacturing processes to service performance.

References

[1] Ning Shunlu. Research on the Prediction Method of Interlayer Fatigue Life of Cord-Rubber Composite Materials. 2025. Harbin Institute of Technology, MA thesis.

[2] Han Hongli. Fatigue Life Prediction of Double-Layer Armored Dynamic Cables Considering Interlayer Friction and Wear. 2023. China University of Petroleum (Beijing), MA thesis.

[3] Ding Xianwang. Study on the Thermo-Mechanical Coupling Behavior and Key Influencing Factors of Wheel-Rail Sliding Contact. 2023. Southwest Jiaotong University, MA thesis.

[4] Sun Yaoliang. Research on a Fast Prediction Method for Wheel-Rail Rolling Contact Fatigue Based on the Shakedown Map and Potential Function. 2022. Southwest Jiaotong University, MA thesis.

[5] Li Hailong. Study on the Influence of Medium on Thermal-Mechanical Damage during Wheel-Rail Sliding Contact. 2021. Lanzhou Jiaotong University, MA thesis.

[6] Chen Jinjing. Fatigue Life Analysis and Experimental Study of the Transmission Mechanism of a Column-Type Electric Power Steering System. 2020. Chongqing University of Technology, MA thesis.