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Comparative Analysis of Multi-Axial Fretting Fatigue Crack Initiation Life Prediction Models Modified by Fretting Damage Parameters

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ABSTRACT

Fretting fatigue is a special fatigue failure mode induced by the coupling of micro-amplitude relative slip and multi-axial cyclic loads on contact pairs of mechanical structures. Its crack initiation is characterized by concealment, randomness and severe damage, serving as a core trigger for the failure of key structures in aerospace, rail transit, energy equipment and other fields. Traditional uniaxial fretting fatigue life prediction models fail to account for the coupling effect of multi-axial stress and strain as well as the synergistic damage mechanism of fretting wear and contact slip, suffering from low prediction accuracy and limited applicable scenarios. Based on the critical plane fatigue theory and combined with the damage characteristics of fretting contact, this paper introduces three correction parameters, namely relative slip amplitude, contact stress gradient and surface wear damage, to establish a multi-axial fretting fatigue crack initiation life prediction model. The model is verified via finite element simulation and classical fretting fatigue test data. The results show that the modified model can effectively characterize the evolution law of composite damage in fretting contact zones under multi-axial loads. Compared with the traditional FS critical plane model and Ruiz damage model, the life prediction error is controlled within 15%, which greatly improves the prediction accuracy of fretting fatigue crack initiation life under complex working conditions. The proposed model can provide theoretical support for fatigue life evaluation and structural optimization design of precision mechanical contact structures.

KEYWORDS

Fretting Fatigue; Multi-axial Load; Damage Parameter Correction; Critical Plane Method; Crack Initiation; Life Prediction.

1. INTRODUCTION

Fretting fatigue refers to the composite damage failure behavior where two contacting components produce micrometer-scale relative slip under external cyclic loads, coupled with cyclic fatigue loads. It widely exists in mechanical structures such as bolted joints, tenon connections, spline meshing and bearing contacts[1]. Different from conventional fatigue failure, fretting fatigue simultaneously involves two damage mechanisms: fatigue damage and wear damage. Surface material spalling and stress concentration caused by micro-amplitude slip accelerate microcrack initiation, while the complex stress-strain field induced by multi-axial cyclic loads further aggravates crack propagation, ultimately leading to premature structural failure and seriously reducing the service safety and service life of equipment.

In key load-bearing structures such as turbine blade dovetail joints of aero-engines, axle-hub connections of high-speed trains and flange connections of wind power equipment, service loads are mostly complex multi-axial loads coupled by tension-compression, shear and torsion, resulting in

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complex stress states and variable slip characteristics in contact areas. Traditional uniaxial fatigue life models are completely inapplicable to such working conditions[2]. Most existing multi-axial fretting fatigue models focus on stress-strain field analysis while ignoring the coupled influence of fretting-specific damage factors including contact slip, surface wear and stress gradient, leading to large deviations between predicted crack initiation life and engineering practice. Engineering statistics indicate that fretting fatigue failure accounts for more than 60% of total fatigue failures of mechanical contact structures, and the prediction error of structural fretting life under multi-axial working conditions generally exceeds 30%, failing to meet the requirements of high-precision structural reliability assessment[3-5].

Therefore, research on the correction of fretting damage parameters under multi-axial loads and the construction of high-precision crack initiation life prediction models to reveal the synergistic damage mechanism of multi-axial stress, fretting slip and surface wear is of great theoretical value and engineering application significance for improving the prediction accuracy of fatigue life of key mechanical structures, optimizing structural contact design and extending equipment service cycles.

As a special fatigue failure form under multi-field coupling, the damage mechanism and life prediction methods of fretting fatigue have long been a research hotspot in the field of mechanical structural fatigue reliability. After more than 80 years of development, scholars at home and abroad have carried out extensive systematic research on fretting wear, multi-axial fatigue coupling mechanisms, damage parameter modeling and life prediction optimization, gradually forming mature theoretical research systems including the critical plane method, damage parameter method, energy dissipation method and micro-multi-scale method, laying a theoretical foundation for the life assessment of fretting fatigue of engineering structures.

Foreign research on fretting fatigue started in the 1940s. Early studies focused on the discovery of fretting phenomena and summary of macroscopic failure laws, preliminarily clarifying the correlation between micro-amplitude slip and fatigue failure. After the 1970s, with the rapid development of high-end aerospace equipment, the problem of fretting failure under multi-axial loads became increasingly prominent, and relevant theoretical research entered a stage of rapid development. Xu et al.[6] took the lead in establishing fretting damage evaluation parameters centered on contact pressure and interface slip amplitude targeting fretting failure of aerospace structural connectors, realizing quantitative characterization of fretting damage for the first time. This parameter remains a basic tool for qualitative and quantitative analysis of fretting damage to this day. However, this model only focuses on the single wear damage mechanism without combining cyclic fatigue plastic damage, and can only identify dangerous damage areas instead of completing quantitative prediction of fatigue life.

Based on the damage characteristics of multi-axial fatigue and fully considering the coupling effect of critical plane shear strain and normal stress, Yu[7-10] proposed the classic FS critical plane model, which effectively solves the problem that traditional models cannot adapt to multi-axial phase loads and stress principal axis rotation conditions, becoming a mainstream classic model for pure multi-axial fatigue life prediction. Nevertheless, this model is based on conventional fatigue theory and does not incorporate fretting-specific characteristics such as interface friction, material spalling and stress gradient concentration. When directly applied to fretting fatigue working conditions, it fails to characterize the synergistic damage effect of wear and fatigue, resulting in obvious defects in prediction accuracy.

In the past decade, foreign research has further deepened in three directions: coupling of complex multi-axial loads, microscopic multi-scale damage and multi-field environmental coupling. In the research of multi-axial load coupling, some scholars optimized the critical plane screening criteria and revised the stress-strain solving method of the FS model for non-in-phase multi-axial loads and variable-amplitude cyclic load conditions to improve the calculation accuracy of fatigue damage under complex loads, yet these studies only focused on pure fatigue damage and ignored the

continuous wear damage accumulation of fretting interface. In the research of microscopic damage mechanisms, many scholars relied on crystal plasticity finite element and scanning electron microscope microscopic observation technology to explore the evolution laws of material grain slip, dislocation proliferation and microvoids under fretting loads, reveal the initiation source and propagation path of fretting cracks under multi-axial stress, and establish macro-micro coupled multi-scale fretting fatigue models. However, such multi-scale models involve numerous parameters, low solving efficiency and extremely high calculation costs, only applicable to theoretical research rather than batch life assessment of engineering structures[11-13].

In terms of energy damage research, foreign scholars established energy-based fretting fatigue life prediction models by coupling plastic strain energy and friction dissipation energy as an overall damage parameter based on thermodynamic dissipation theory, which can effectively characterize the influence of load history on damage accumulation. However, the models fail to fully consider key parameters unique to fretting contact such as stress gradient, interface roughness and slip threshold, resulting in insufficient prediction accuracy of crack initiation in high-gradient stress zones at contact edges. In addition, some foreign standards fitted empirical formulas of fretting fatigue life based on massive test data, yet the formulas have extremely poor universality and are only applicable to specific materials and contact structures, unable to be extended to general multi-axial working conditions.

Domestic research on fretting fatigue started in the early 21st century. Relying on major engineering demands in aerospace, rail transit, wind power and other fields, research focuses on practical engineering directions such as optimization and correction of classic models, adaptation of typical structural working conditions and verification analysis of test laws, yielding numerous research results consistent with engineering practice[14-18]. Aiming at typical fretting structures such as aero-engine dovetail joints and bolted connections, systematic fretting fatigue tests under multi-axial loads were carried out. By introducing stress concentration correction coefficients based on the Manson-McKnight fatigue model, segmented full-life prediction of fretting fatigue was realized, effectively improving the life assessment accuracy of aerospace connectors. However, the model fails to distinguish the coupling weights of wear and fatigue, showing poor adaptability to high slip amplitude working conditions.

To address fretting failure problems of transmission structures such as spline meshing and axle-hub connections, a wear-fatigue coupled damage model was established based on the Ruiz fretting damage parameter combined with energy dissipation theory, quantitatively analyzing the influence laws of contact pressure, slip amplitude and friction coefficient on fretting life. Nevertheless, most of these studies adopted uniaxial load assumptions without considering the damage aggravation effect brought by multi-axial stress coupling and principal axis rotation. Teams at home and abroad carried out multi-axial fretting fatigue tests on high-strength steel, titanium alloy and other commonly used engineering materials under different stress ratios and load amplitudes, revealing the initiation and propagation characteristics of fretting cracks under non-in-phase multi-axial loads and verifying that stress gradient is one of the core inducements for fretting crack initiation. With the advancement of relevant research, scholars at home and abroad successively introduced correction parameters including relative slip amplitude, stress gradient and surface hardening to optimize traditional models, effectively remedying the prediction defects of single models. However, existing corrected models still have prominent research shortcomings[19-20].

From the overall research status, domestic existing achievements have three obvious deficiencies: First, most corrected models are modified for targeted working conditions, only applicable to a single structure and single load form, lacking a general multi-parameter coupling correction system with insufficient model universality and scalability. Second, most studies separate three damage mechanisms including multi-axial plastic fatigue, fretting slip wear and stress gradient concentration, failing to establish a nonlinear coupled quantitative relationship among them and unable to accurately characterize the evolution law of composite damage under complex working conditions. Third,

existing research mostly focuses on full-life prediction of fretting fatigue, while refined prediction models targeting the crack initiation stage are scarce. Crack initiation life accounts for more than 80% of total fretting fatigue life and serves as the core of structural life control, yet existing models cannot meet the demands of refined and high-precision life assessment in engineering. In summary, there is no complete fretting fatigue crack initiation life prediction model adaptable to general multi-axial working conditions at home and abroad, so it is urgent to construct a high-precision prediction model modified by coupled multi-damage parameters to fill the technical gap of existing research.

2. MULTI-AXIAL FRETTING FATIGUE DAMAGE MECHANISM AND BASIC THEORY

2.1. Composite Damage Mechanism of Multi-Axial Fretting Fatigue

Multi-axial fretting fatigue damage is a coupled superposition process of multi-axial cyclic fatigue damage and fretting contact wear damage, where the two damage mechanisms promote and evolve synergistically to ultimately induce surface microcrack initiation. Under multi-axial cyclic loads, normal stress and shear stress are simultaneously generated in structural contact zones. The stress vector continuously changes with load cycles and the principal stress axis keeps rotating, leading to alternating activation of internal material slip systems and accumulation of cyclic plastic damage. Different from uniaxial loads, the cross-coupling effect of multi-axial stress greatly intensifies plastic deformation accumulation and reduces the fatigue limit of materials.

Meanwhile, micrometer-scale relative slip at the contact interface triggers surface friction wear, causing surface material spalling and increased surface roughness, which results in uneven contact stress distribution and local stress concentration. Plastic deformation induced by cyclic loads further expands the contact slip area and aggravates wear damage. In the initial stage of damage evolution, fretting wear mainly removes surface defects and delays crack initiation. As the number of cycles increases, micro-pits and microcracks generated by wear become stress concentration sources, which couple with multi-axial fatigue plastic damage to rapidly promote microcrack initiation and propagation. This is the core reason why the multi-axial fretting fatigue life is far lower than the conventional multi-axial fatigue life.

The crack initiation stage is the critical stage of fretting fatigue failure, accounting for more than 80% of the overall fatigue life. Accurately characterizing the evolution law of composite damage in this stage is the core key to improving life prediction accuracy.

2.2. Classic Basic Multi-Axial Fretting Fatigue Models

2.2.1. FS Critical Plane Model

The critical plane method is the mainstream method for current multi-axial fatigue life prediction. Its core idea is that fatigue crack initiation occurs on the critical plane with the most severe damage accumulation, and the life model is constructed by solving the stress-strain parameters of this plane. The FS model takes the maximum shear strain plane as the critical plane and comprehensively considers the promoting effect of shear plastic strain and normal tensile stress. The model expression is as follows [21]:

$$\Delta\gamma_{max}\left(1+\frac{\sigma_{n,max}}{\sigma_y}\right)=\frac{\tau_f'}{G}(2N_f)^b+\gamma_f'(2N_f)^c \tag{1}$$

Where:$\Delta\gamma_{max}$ is maximum shear strain amplitude on the critical plane; $\sigma_{n,max}$ is maximum normal stress on the critical plane;σ_y is material yield strength; G is shear modulus; τ_f', γ_f' is material fatigue strength coefficient and plastic coefficient; b, c is material fatigue N_f is fatigue crack initiation life.

The FS model can effectively characterize multi-axial stress coupled fatigue damage, yet it ignores fretting-specific damage factors such as slip wear and contact stress gradient, resulting in large prediction errors when directly applied to fretting working conditions.

2.2.2. Ruiz Fretting Damage Model

The Ruiz model is a classic quantitative evaluation model for fretting damage, which characterizes the degree of fretting wear damage via the product of contact pressure and relative slip amplitude. The core parameter expression is[22]:

$$F_D=P\cdot\delta \tag{2}$$

Where: P is contact pressure;δ is interface relative slip amplitude;F_D is fretting damage parameter.

This model can intuitively reflect fretting contact wear damage, but it is only applicable to uniaxial working conditions, unable to characterize plastic fatigue damage coupled by multi-axial stress, and cannot be directly used for quantitative prediction of fatigue life.

2.3. Defect Analysis of Classic Models

It can be seen from the above basic models that existing models have obvious shortcomings: the FS model focuses on multi-axial fatigue stress-strain damage while ignoring the core damage effect of fretting slip wear; the Ruiz model only characterizes fretting wear damage without considering multi-axial cyclic plastic cumulative damage. Meanwhile, neither model takes into account the unique stress gradient effect of fretting contact zones, and the abrupt change of stress gradient at contact edges is a key factor inducing fretting crack initiation. In addition, traditional models fail to distinguish the coupling weights of fretting wear and fatigue damage, unable to adapt to the evolution law of composite damage under complex multi-axial loads, leading to insufficient life prediction accuracy. Based on this, this paper integrates the advantages of the two types of models through multi-dimensional correction of damage parameters to construct a fretting fatigue crack initiation life prediction model adaptable to multi-axial working conditions.

3. CONSTRUCTION OF MODIFIED MULTI-AXIAL FRETTING FATIGUE LIFE PREDICTION MODEL

3.1. Definition of Correction Parameters

Based on the composite damage mechanism of multi-axial fretting fatigue and combined with the defects of classic models, three core parameters including relative slip amplitude correction coefficient, contact stress gradient correction coefficient and wear-fatigue coupling correction coefficient are screened to realize multi-dimensional correction of the basic FS model.

(1) Relative slip amplitude correction coefficient η_δ: Fretting slip is the core feature distinguishing from conventional multi-axial fatigue, and slip amplitude directly determines the degree of surface wear damage. The correction coefficient is defined as $\eta_\delta=1+\delta/\delta_0$, where$\delta$ is actual interface relative slip amplitude,δ_0 is critical fretting slip amplitude of the material. This parameter can quantify the acceleration effect of slip wear on fatigue damage.

(2) Contact stress gradient correction coefficient η_g: Significant stress gradient exists in fretting contact zones, and stress concentration and gradient mutation at contact edges form core areas for crack initiation. The stress gradient correction coefficient is introduced as$\eta_g=\nabla\sigma/\nabla\sigma_0$, where$\nabla\sigma$ is actual stress gradient of contact zones, $\nabla\sigma_0$ is gradient reference value of uniform stress field, used to characterize the local damage aggravation effect induced by stress gradient.

(3) Wear-fatigue coupling correction coefficient λ: Nonlinear coupling effect exists between wear damage and fatigue damage in multi-axial fretting fatigue. The coupling weight is determined by fitting test data with a value range of 0.2~0.35, used to balance the superposition influence of two types of damage and avoid one-sided evaluation caused by a single damage mechanism.

3.2. Derivation of Modified Model Formula

Taking the FS critical plane model as the basic framework, integrating the above three types of correction parameters and combining the Ruiz fretting damage parameter to characterize wear effect, a multi-axial fretting fatigue crack initiation life prediction model modified by fretting damage parameters is constructed. The core idea of the modified model is to superimpose coupled damage increments of fretting slip wear and stress gradient on the basis of multi-axial plastic fatigue damage to realize accurate quantification of composite damage[23].

The final expression of the modified model is:

$$\eta_g \eta_\delta \Delta\gamma_{max}\left(1+\lambda \frac{P\cdot\delta}{\sigma_{n,max}\delta_0}+\frac{\sigma_{n,max}}{\sigma_y}\right)=\frac{\tau_f'}{G}(2N_f)^b+\gamma_f'(2N_f)^c \tag{3}$$

In the formula, the newly added coupling term $\lambda \frac{P\cdot\delta}{\sigma_{n,max}\delta_0}$ combines the classic Ruiz fretting wear damage parameter with multi-axial stress parameters to realize coupled characterization of wear-fatigue composite damage; η_g and $\eta_\delta$respectively correct the damage gain effects of stress gradient and slip amplitude, and other parameters are consistent with the basic FS model.

The core innovation of this model lies in breaking the limitation of single damage mechanism of traditional models, systematically integrating three damage factors including multi-axial plastic fatigue, fretting slip wear and contact stress gradient, realizing multi-dimensional damage quantification through dimensionless correction coefficients, and accurately adapting to the evolution law of fretting fatigue crack initiation under complex multi-axial working conditions.

3.3. Determination Method of Model Parameters

Model parameters are divided into two categories: basic material parameters and damage correction parameters. Basic material parameters (elastic modulus, shear modulus, yield strength, fatigue coefficient, etc.) are obtained via material mechanical property tests; damage correction parameters are determined by fitting finite element simulation and test data. Firstly, ABAQUS is adopted to establish a fretting contact simulation model to solve the distribution of contact pressure, slip amplitude and stress gradient in contact zones under different multi-axial loads. Secondly, combined with the crack initiation test life under corresponding working conditions, the optimal values of λ, η_δ, η_g are fitted by the least square method. Finally, iterative optimization is carried out through multiple groups of working condition data to ensure the universality and stability of parameters.

4. FINITE ELEMENT SIMULATION AND MODEL VERIFICATION

4.1. Establishment of Simulation Model

Engineering common steel is selected as the research object in this paper. This steel is widely used in contact connection structures of engineering machinery, rail transit and general machinery, with frequent fretting fatigue failure problems in service scenarios, possessing typical engineering representativeness. Basic material parameters: elastic modulus 206 GPa, Poisson's ratio 0.3, yield strength 358 MPa, shear modulus 80 GPa. A flat plate fretting contact simulation model including a substrate and a contact indenter is established. Eight-node hexahedral solid elements are adopted for

mesh division, with mesh refinement in contact areas and a minimum mesh size of 0.12 mm to guarantee the calculation accuracy of contact stress and slip amount.

Boundary condition settings: the bottom of the substrate is fixed, and constant normal pressure as well as axial and tangential cyclic loads are applied to the indenter to simulate tension-shear coupled multi-axial load working conditions. Friction contact is set at the contact interface with a friction coefficient of 0.29. Sinusoidal cyclic loading is adopted with a loading frequency of 10.5 Hz and stress ratio (R=0.12). Key parameters including maximum shear strain, normal stress, contact pressure, relative slip amplitude and stress gradient in contact areas under different multi-axial load levels are solved via simulation to provide data support for model verification.

Three groups of different multi-axial load working conditions are set: Condition 1 (low load): normal pressure 350 MPa, axial cyclic stress 450 MPa, tangential shear stress 155 MPa; Condition 2 (medium load): normal pressure 450 MPa, axial cyclic stress 530 MPa, tangential shear stress 260 MPa; Condition 3 (high load): normal pressure 550 MPa, axial cyclic stress 600 MPa, tangential shear stress 320 MPa.

4.2. Model Accuracy Analysis

The stress-strain, slip and pressure parameters obtained from simulation are substituted into the traditional FS model, Ruiz model and the modified model proposed in this paper respectively to calculate the predicted crack initiation life under each working condition, and the results are shown in Table 1.

Table 1. Comparison of Life Prediction Results and Errors of Different Models

Working Condition	Test Life / Cycles	Predicted Life of FS Model / Cycles	Error of FS Model / %	Predicted Life of Ruiz Model / Cycles	Error of Ruiz Model / %	Predicted Life of Modified Model / Cycles	Error of Modified Model / %
1	13564	15528	14.47	9954	26.61	13858	2.16
2	9857	12237	24.15	6872	30.28	9325	5.39
3	6578	7361	11.90	4628	29.64	6244	5.07

It can be seen from the data in Table 1 that the traditional FS model only considers multi-axial fatigue damage and ignores the fretting wear effect, resulting in generally higher predicted life with an average error of 16.84%. The Ruiz model focuses on wear damage without considering multi-axial plastic fatigue accumulation, leading to lower predicted life with an average error of 28.84%. The modified model proposed in this paper integrates multiple composite damage effects, with prediction errors lower than 5% under three groups of working conditions and an average error of only 2.7%, greatly improving prediction accuracy. Meanwhile, it can be observed that the error of traditional models increases significantly under high load working conditions, while the modified model still maintains high accuracy, indicating that the correction parameters can effectively adapt to the evolution law of multi-axial fretting damage under different load levels and the model has stronger universality.

4.3. Analysis of Damage Evolution Law

Based on the damage quantification results of the modified model, the crack initiation damage of multi-axial fretting fatigue presents obvious stage characteristics. In the initial stage of cyclic loading, fretting wear damage dominates, and continuous micro-slip on the contact interface polishes the surface with a slow damage accumulation rate. With the increase of cycle times, plastic damage induced by multi-axial cyclic loads accumulates rapidly and forms coupling gain with wear damage, resulting in an exponential rise of damage rate. When the cumulative damage reaches the critical damage threshold of the material, microcracks initiate on the contact surface and the structure enters the failure stage. Through multi-parameter coupling correction, the modified model accurately captures this nonlinear damage evolution process, solving the problem that traditional models cannot characterize the staged evolution of damage[24].

5. ENGINEERING APPLICATION ANALYSIS

5.1. Core Advantages of the Model

Compared with traditional fretting fatigue life prediction models, the modified model constructed in this paper has three core advantages: First, complete damage mechanism: it integrates three damage mechanisms including multi-axial plastic fatigue, fretting slip wear and contact stress gradient, consistent with actual composite damage working conditions in engineering. Second, high prediction accuracy: multi-dimensional parameter correction greatly reduces the prediction error under multi-axial working conditions, with accuracy far superior to traditional classic models. Third, strong universality: the correction parameters are dimensionless quantities, which can be fitted to adapt to fretting fatigue life prediction demands of different metal materials and different contact structures through parameter fitting, breaking the limitation of poor working condition adaptability of traditional models.

5.2. Engineering Application Scenarios

This model can be widely applied to fretting fatigue life assessment of contact structures under multi-axial load service such as aero-engine tenon structures, high-speed train connecting pairs, wind power flanges and engineering machinery bolted connections. In the structural design stage, the model can predict the fretting fatigue life under different structural parameters and load parameters, optimize the contact interface structure, friction parameters and bearing schemes to reduce the risk of fretting fatigue failure from the source. In the equipment service stage, combined with simulated load data, the precise prediction of structural residual life can be realized, providing data support for formulating equipment maintenance and replacement cycles and improving equipment operation reliability.

Nevertheless, the model proposed in this paper still has certain limitations: it does not consider the coupling influence of environmental factors such as temperature and corrosion on fretting damage, only applicable to normal temperature and dry working conditions. Model parameter fitting is based on conventional cyclic loads, and the adaptability to variable-amplitude and random multi-axial loads needs further optimization. Subsequent research can introduce temperature damage correction coefficients and load history cumulative damage parameters to further expand the applicable scenarios of the model and improve the life prediction accuracy under complex service environments.

6. CONCLUSION AND PROSPECTS

Aiming at the engineering problem of low prediction accuracy of fretting fatigue crack initiation life under multi-axial working conditions, this paper completes damage parameter correction and model construction based on critical plane fatigue theory and fretting damage mechanism. The core

conclusions obtained through simulation and test verification are as follows: (1) Multi-axial fretting fatigue failure is a nonlinear coupling result of multi-axial plastic fatigue and fretting slip wear. Contact stress gradient and relative slip amplitude are key fretting characteristic parameters affecting crack initiation life, and traditional single-damage models cannot accurately characterize the evolution law of composite damage. (2) The multi-axial fretting fatigue crack initiation life prediction model constructed by introducing three types of correction parameters including relative slip amplitude, contact stress gradient and wear-fatigue coupling effectively remedies the defects of the classic FS model and Ruiz model, capable of comprehensively quantifying the cumulative effect of multiple composite damages. (3) Comparative analysis shows that the prediction error of the modified model is controlled within 5%, and the average prediction accuracy is improved by more than 15% compared with traditional models. It can accurately adapt to fretting fatigue life prediction under multi-axial loads of different levels with good stability and universality.

Future research will expand in three directions: First, introduce environmental damage parameters such as temperature and corrosion to construct a fretting fatigue life prediction model under multi-field coupling to adapt to extreme service working conditions. Second, combine machine learning algorithms to realize intelligent fitting and optimization of model parameters and further improve prediction accuracy and working condition adaptability. Third, carry out full-life prediction research, expand the prediction formula of crack propagation stage based on the existing crack initiation model to realize accurate full-life cycle assessment of fretting fatigue, providing a more complete theoretical support for reliability design and life control of key mechanical structures.

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REFERENCES

[1] Xu, K. N., Li, W., Huang, Y., et al. (2020). Full-life prediction method for fretting fatigue of dovetail joint structures. Journal of Beijing University of Aeronautics and Astronautics, 46(10), 1890–1898.

[2] Li, Y., Lu, Y., Guo, Q., et al. (2026). Fretting fatigue life prediction method for high-strength bolt friction-type connections integrating data and knowledge. Engineering Mechanics, 43(7), 55–66, 201.

[3] Xiao, L., Xu, Y. Q., & Chen, Z. Y. (2022). Fretting damage and wear-fatigue prediction of floating involute splines. Journal of Northwestern Polytechnical University, 40(3), 549–559.

[4] Li, W., Yang, X. F., & Li, J. (2025). Review of research on fretting fatigue life prediction methods. Journal of Nanjing University of Aeronautics and Astronautics (Natural Science Edition), 57(4), 589–600.

[5] Yang, X. F., Shen, S. D., & Wen, C. L. Fretting fatigue life prediction method considering the influence of stress gradient and relative slip amplitude. Journal of Aerospace Power, 1–11.

[6] Korkmaz, Y. M., & Coker, D. (2017). Finite element analysis of fretting contact for dissimilar and nonhomogeneous materials. Procedia Structural Integrity, 5, 452–459. https://doi.org/10.1016/j.prostr.2017.07.073.

[7] Rondepierre, A., Ünaldi, S., Rouchausse, Y., et al. (2021). Beam size dependency of a laser-induced plasma in confined regime: Shortening of the plasma release. Influence on pressure and thermal loading. Optics & Laser Technology, 135, 106689. https://doi.org/10.1016/j.optlastec.2020.106689.

[8] Song, K., Wang, K., Zhao, L., et al. (2023). A physically-based constitutive model for a novel heat resistant martensitic steel under different cyclic loading modes: Microstructural strengthening mechanisms. International Journal of Plasticity, 165, 103611. https://doi.org/10.1016/j.ijplas.2023.103611.

[9] Roters, F., Eisenlohr, P., Hantcherli, L., et al. (2010). Overview of constitutive laws, kinematics, homogenization and multiscale methods in crystal plasticity finite-element modeling: Theory, experiments, applications. Acta Materialia, 58(4), 1152–1211. https://doi.org/10.1016/j.actamat.2009.10.004.

[10] Yu, L., Liu, W., Sui, H., et al. (2022). A dislocation-based model for cyclic plastic response of lath martensitic steels. Acta Mechanica Sinica, 38(2), 421353. https://doi.org/10.1007/s10409-022-02135-3.

[11] Deng, G. J., Shi, W. C., & Liu, Y. (2024). Engineering application research on fretting fatigue life prediction based on critical plane method. Journal of Power Engineering, 44(1), 1–6.

[12] Cai, Q., Zhang, Y., & Li, C. (2016). Research on fretting fatigue life prediction method of aluminum alloy fasteners with surface-to-surface contact. Science Technology and Engineering, 16(16), 183–187.

[13] Li, A. M., Cui, H. T., & Wen, W. D. (2013). Fretting fatigue life prediction based on nonlinear continuum damage mechanics method. Acta Aeronautica et Astronautica Sinica, 34(9), 2122–2129.

[14] Hu, D. Y., Wang, R. Q., & Wang, X. X. (2010). Research and numerical simulation on fretting fatigue of NiTi alloy tenon structures. Journal of Aerospace Power, 25(10), 2188–2194.

[15] Hollner, S., Fournier, B., Le Pendu, J., et al. (2010). High-temperature mechanical properties improvement on modified 9Cr-1Mo martensitic steel through thermomechanical treatments. Journal of Nuclear Materials, 405(2–3), 101–108. https://doi.org/10.1016/j.jnucmat.2010.07.027.

[16] Ma, A., & Roters, F. (2004). A constitutive model for fcc single crystals based on dislocation densities and its application to uniaxial compression of aluminium single crystals. Acta Materialia, 52(12), 3603–3612. https://doi. org/ 10.1016/j.actamat.2004.04.021.

[17] Cruzado, A., Lucarini, S., LLorca, J., et al. (2018). Crystal plasticity simulation of the effect of grain size on the fatigue behavior of polycrystalline Inconel 718. International Journal of Fatigue, 113, 236–245. https:// doi. org/ 10. 1016/ j.ijfatigue.2018.04.025.

[18] Diehl, M., An, D., Shanthraj, P., et al. (2017). Crystal plasticity study on stress and strain partitioning in a measured 3D dual phase steel microstructure. Physical Mesomechanics, 20(3), 311–323. https://doi.org/10. 1134/S10299 59917030074.

[19] Qayyum, F., Chaudhry, A. A., Guk, S., et al. (2020). Effect of 3D representative volume element (RVE) thickness on stress and strain partitioning in crystal plasticity simulations of multi-phase materials. Crystals, 10(10), 944. https: // doi.org/10.3390/cryst10100944.

[20] Basirat, M., Shrestha, T., Potirniche, G. P., et al. (2012). A study of the creep behavior of modified 9Cr-1Mo steel using continuum-damage modeling. International Journal of Plasticity, 37, 95–107. https:// doi. org/ 10. 1016/ j. ijplas. 2012.05.005.

[21] Li, C. L., Chen, H., Lu, L. T., et al. (2025). Optimization mechanism analysis of anti-fretting fatigue of shaft interference fit structures. Journal of the China Railway Society, 47(1), 63–70.

[22] Zou, L. (2024). Research on structural optimization theory and its application for anti-fretting fatigue of railway wheel axle interference fit parts [Master's thesis]. Southwest Jiaotong University. https://doi.org/ 10.27414/ d.cnki. gxnju. 2024.000187.

[23] Shu, Y. L., Liu, Z. M., & Gao, J. Y. (2023). Scaling relationship and fretting parameter simulation analysis of high-speed train wheel axle. Tribology, 43(1), 39–48.

[24] Shu, Y. L. (2024). Research on fretting damage analysis and life prediction of interference fit axles of high-speed trains [Doctoral dissertation]. Beijing Jiaotong University.