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Review on Ultra-High-Cycle Fretting Fatigue Damage Mechanism of Press-Fitted Structure of Wheel Axles

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Abstract: As the core load-bearing components of high-speed train running gears, electric multiple unit (EMU) wheel axles are generally connected by interference press-fitting, and their service reliability directly determines the train operation safety. During the long-term high-frequency and long-mileage service of EMUs, the press-fit interface of wheel axles generates micron-scale reciprocating micro-slip under the coupling effect of rotating bending alternating load, wheel-rail impact load and random line vibration, inducing coupled damage of fretting wear and fretting fatigue. Different from conventional mechanical fatigue, the cumulative service load cycles of wheel axles can reach 108 ~ 109 in the ultra-high-cycle range. The fretting effect completely eliminates the traditional fatigue limit of steel materials, and concealed multi-source short cracks continuously initiate and propagate under low-stress and ultra-high-cycle conditions, which is extremely easy to cause sudden failure of wheel axles without obvious precursors. This paper systematically summarizes the interface zoning characteristics, macroscopic failure laws and microscopic damage evolution mechanisms of ultra-high-cycle fretting fatigue of press-fitted EMU wheel axles. The domestic and foreign research progress is reviewed from four dimensions including experimental characterization, numerical simulation, life prediction and anti-damage technology. Furthermore, the key scientific and engineering problems in current research, such as the wear-crack competition mechanism, scale effect, random load damage accumulation and early damage identification are deeply analyzed. Combined with the operation and maintenance requirements of high-speed trains, the future development directions of multi-scale mechanism research, load-adaptive life models, intelligent simulation and active protection technology are clarified. This study aims to improve the theoretical system of ultra-high-cycle fretting fatigue of high-speed wheel axles, and provide theoretical support and technical reference for structural optimization, assembly process upgrading, service damage evaluation and full-life-cycle safety operation and maintenance of EMU wheel axles.

Keywords: EMU wheel axle, interference press-fitting, fretting fatigue, ultra-high-cycle fatigue, micro-slip, damage evolution, life prediction, interface coupling damage.

1. Introduction

China ranks first in the world in terms of high-speed railway network scale, operating mileage and departure density. Fuxing series EMUs have realized normalized high-density and long-term service, putting forward extremely high requirements for the long-life and high-reliability performance of core running gear components. As the key load-bearing and transmission structure of EMUs, the wheel axle system bears vehicle body loads, transmits traction and braking forces, and adapts to wheel-rail contact motion. Its structural integrity and fatigue reliability are directly related to train operation safety. At present, wheel and axle assemblies of domestic and foreign EMUs adopt interference press-fitting connection, which realizes keyless rigid connection relying on radial contact compressive stress generated by assembly interference. With the advantages of simple structure, high bearing capacity and stable transmission, it has become the mainstream assembly form for high-speed wheel axles [1].

Under ideal static conditions, the press-fit interface is closely attached without relative slip, and the structural service state remains stable [2]. However, in actual high-speed service conditions, the wheel axle is continuously subjected to complex coupled loads such as high-speed rotating bending load, impact load from track joints and turnouts, vehicle body vibration and wind disturbance. The elastic deformation curvature of the wheel seat and hub is inconsistent, resulting in micron-scale reciprocating micro-slip on the originally tightly fitted press-fit interface, which induces typical fretting damage effect. Fretting damage is not a single wear or fatigue problem, but a multi-field coupled damage behavior integrating tribology, material mechanics, solid mechanics and environmental chemistry, including three forms of fretting wear, fretting corrosion and fretting fatigue. The three mechanisms compete and cooperate with each other, eventually leading to structural performance degradation and failure [3].

Traditional mechanical fatigue theory takes 107 cycles as the fatigue limit threshold, holding that metal materials will not suffer fatigue failure under stress lower than this threshold, which is widely applied in the fatigue design and verification of traditional mechanical components. Nevertheless, the service life of high-speed EMU wheel axles can reach several decades, with cumulative load cycles up to 108~109, which belongs entirely to the ultra-high-cycle fatigue category. A large number of engineering practices and experimental studies have verified that the coupling of fretting and ultra-high-cycle loads completely breaks the traditional fatigue limit of metal materials. Even if the load stress is far lower than the conventional fatigue design threshold, micro-cracks will still initiate and propagate continuously on the press-fit interface after billions of cyclic accumulations, eventually causing wheel axle fracture failure. Compared with conventional fatigue, ultra-high-cycle fretting fatigue damage is characterized by strong concealment, multi-source crack initiation, large damage dispersion and no obvious failure precursors, and early micron-scale damage is difficult to identify by conventional non-destructive testing methods, becoming a core hidden danger threatening the long-term safe service of EMUs.

In recent years, scholars at home and abroad have carried out extensive research on fretting fatigue of railway press-fitted wheel axles, clarified the interface zoning characteristics, basic damage forms and macroscopic failure laws of press-fit structures, and formed a research system combining experimental testing and numerical simulation. However, existing studies mostly focus on medium and low-cycle fretting fatigue within 107 cycles, and there are obvious deficiencies in key issues such as the wear-crack competition mechanism in the ultra-high-cycle range, damage accumulation law under random loads, scale effect conversion between scaled models and physical components, and quantitative identification of early micro-damage [4]. Based on the above research status, this paper systematically summarizes the failure characteristics, microscopic damage mechanism and domestic and foreign research progress of ultra-high-cycle fretting fatigue of EMU press-fitted wheel axles, analyzes the existing core problems, and prospects the key research priorities and engineering application directions, so as to provide theoretical support for the anti-fretting fatigue design, life evaluation and operation and maintenance system improvement of high-speed wheel axles.

2. Failure Characteristics of Ultra-High-Cycle Fretting Fatigue of Press-Fitted Wheel Axles

2.1. Zoning Distribution Characteristics of Press-Fit Interface Fretting

The fretting behavior of the interference press-fit interface of EMU wheel axles presents significant regional differences. Under rotating bending load, the matching surface of wheel seat and hub shows a three-zone distribution from the edge to the center, namely complete slip zone, mixed slip zone and adhesion zone. This zoning mode is the core factor determining the location and degree of fretting damage, and also the mechanical basis for the unique failure characteristics of press-fitted wheel axles [5].

The complete slip zone is located at the outermost edge of the press-fit interface, with relatively low contact pressure and the maximum micro-slip amplitude ranging from 10 to 22 μm and intense reciprocating slip [6]. Under long-term cyclic load, the surface material of the interface undergoes severe plastic shear deformation, and the surface oxide film is continuously broken, regenerated and peeled off, generating a large number of reddish-brown iron oxide wear debris. The main damage mechanisms are abrasive wear, oxidative wear and surface delamination damage, dominated by material loss with rare fatigue crack initiation.

The mixed slip zone is the transition annular region between the complete slip zone and the adhesion zone, with a critical slip amplitude and alternating slip and adhesion behaviors, serving as the core area for fretting fatigue crack initiation. Both surface wear damage and subsurface fatigue damage exist in this zone. Micro-pits and furrows caused by wear form local stress concentration and induce micro-crack nucleation, while the initiated micro-cracks may be peeled off by continuous slip wear, forming a dynamic competition relationship between wear and crack growth. The cutting detection results of physical wheel axles show that more than 90% of fatigue cracks on the press-fit interface originate from this zone, presenting typical multi-source and dispersed crack initiation characteristics [7].

The adhesion zone is located in the central area of the press-fit interface with the maximum interference contact pressure and tight interface fitting. There is almost no relative micro-slip, and the surface plastic deformation and friction damage are extremely weak with basically no fretting damage, which serves as the main bearing area of the press-fit structure. The range and morphology of the three zones are mainly determined by assembly interference, interface friction coefficient and external load amplitude. Insufficient interference will expand the slip area and aggravate wear; excessive interference will lead to a sharp increase of edge stress concentration and accelerate crack initiation in the mixed slip zone.

2.2. Differentiated Failure Laws Under Ultra-High-Cycle Conditions

Under ultra-high-cycle fatigue 107~109 cycles) conditions, the fretting fatigue failure law of press-fitted wheel axle structures is essentially different from that of medium and low-cycle fatigue, subverting the applicable boundary of traditional fatigue design theory, which is specifically reflected in four core characteristics [8].

First, there is no traditional fatigue limit. Conventional steel materials tend to stabilize after 107 cycles with a fixed fatigue limit, while under the coupling action of fretting and ultra-high-cycle loads, the fatigue strength of materials decays continuously without a fatigue limit threshold, and fatigue failure still occurs under low-stress and ultra-high-cycle conditions [9]. Relevant tests show that the fretting fatigue strength of wheel axle steel is 30%~50% lower than that of conventional smooth specimens, and the strength attenuation trend becomes more obvious with the increase of cycles.

Second, the damage evolution cycle is long and highly concealed. The life of medium and low-cycle fatigue is mainly consumed in the crack propagation stage, while more than 90% of the life of ultra-high-cycle fretting fatigue is consumed in the micro-crack initiation and short crack propagation stage. In this stage, the crack size is at the micron level without macroscopic cracks, causing no structural deformation or abnormal noise [10]. It is difficult to be identified by conventional operation and maintenance detection, and the cracks propagate latently for a long time until rapid penetration induces sudden fracture.

Third, the failure mode changes from surface damage to subsurface multi-source crack initiation. Medium and low-cycle fretting fatigue cracks mostly originate from surface wear defects, while under ultra-high-cycle cyclic loads, the surface layer of the interface tends to be flat after long-term wear, and the surface stress concentration is gradually weakened [11]. Microscopic damages such as dislocation accumulation, grain distortion and inclusion defects concentrate in the subsurface layer, eventually forming multi-source micro-cracks at subsurface grain boundaries and non-metallic inclusions. Multiple cracks connect in parallel to form main cracks, greatly increasing the failure risk.

Fourth, multi-load coupling aggravates damage dispersion. The service load of EMU wheel axles is not a constant amplitude load, but a random variable amplitude load formed by superposing rotating bending basic load, wheel-rail impact and line irregularity vibration. The interaction of different load sequences and impact amplitudes changes the interface slip state and stress accumulation law, resulting in significantly increased dispersion of ultra-high-cycle fretting fatigue life, and the traditional single life curve cannot accurately characterize the service life [12].

2.3. Full-Life-Cycle Damage Evolution Stages

Combined with the service mileage and load accumulation law of EMU wheel axles, the ultra-high-cycle fretting fatigue damage evolution can be divided into three complete stages with distinct damage characteristics and evolution mechanisms.

The first stage is interface stress relaxation and early wear stage (0~150,000 km). In the initial stage of wheel axle assembly, the interference stress is at the peak state with tight interface fitting [13]. Under initial cyclic loads, the microscopic protrusions on the interface are plastically rolled, the fitting surface stress is redistributed with slight stress relaxation, the micro-slip behavior is gradually activated, and the surface layer produces slight oxidative wear and plastic deformation without micro-crack generation, and the overall structural performance has no obvious attenuation.

The second stage is micro-crack initiation and short crack propagation stage (150,000~1,000,000 km, 107~108 ultra-high cycles). With the continuous increase of cyclic cycles, the mixed slip zone undergoes repeated shear deformation, dislocations continuously proliferate and entangle to form dislocation cells and dislocation walls, resulting in continuous accumulation of local stress. Under the sustained action of ultra-high-cycle loads, microscopic defects gradually evolve into micron-level short cracks, and multi-source cracks initiate independently and expand slowly, which is the core life consumption stage of ultra-high-cycle fretting fatigue [14].

The third stage is long crack penetration and structural failure stage (more than 1,000,000 km, more than 108 cycles). Part of the short cracks break through the propagation threshold and expand radially inward under the driving of alternating bending moment [15]. Multiple short cracks connect and penetrate to form macroscopic main cracks, the effective bearing section of the structure decreases continuously, the stress concentration is further intensified, the crack propagation rate increases rapidly, and finally leads to wheel axle fatigue fracture and structural failure.

3. Ultra-High-Cycle Fretting Fatigue Damage Mechanism of Press-Fitted Wheel Axles

3.1. Formation Mechanism of Interface Micro-Dynamic Behavior

The fretting behavior of interference press-fit structures is essentially the micro-slip effect caused by inconsistent constraint deformation. During wheel axle press-fitting, the wheel hub is pressed into the wheel seat by external force, and the radial interference pre-pressure generated by elastic deformation realizes interface fastening constraint. During train operation, the wheel axle rotates continuously and bears vertical bending load, resulting in elastic deflection deformation of the axle. The hub has higher stiffness and smaller deformation, leading to asynchronous curvature deformation between the wheel seat and hub. Periodic reciprocating relative slip occurs at the edge of the interface contact, with the slip amplitude stably maintained at the micron level, providing the mechanical prerequisite for fretting damage.

The core control parameters of interface fretting behavior include interface contact compressive stress, tangential friction shear stress, micro-slip amplitude, interface friction coefficient and external load amplitude, which couple with each other to jointly determine the damage degree. Assembly interference is the most critical design parameter. Increasing interference can improve the average interface contact pressure, narrow the slip area and effectively restrain macroscopic slip; however, excessive interference will cause a sharp increase of edge stress concentration coefficient, aggravate local plastic accumulation and promote micro-crack initiation; insufficient interference will lead to a significant increase of slip amplitude, aggravate fretting wear, and even cause loose interface fit and reduce structural bearing stability. Therefore, reasonable matching of interference is the core key to balance wear and fatigue damage of press-fitted structures.

3.2. Microscopic Damage Evolution Mechanism

Ultra-high-cycle fretting fatigue is a multi-scale coupled damage process of macroscopic mechanical load, mesoscopic friction and wear, and microscopic structural evolution [16]. Its microscopic evolution mechanism is different from conventional fatigue, characterized by accumulation, gradualness and concealment.

Firstly, cumulative surface plastic deformation occurs. The overall wheel axle remains elastic in service, but the mixed slip zone of the press-fit interface bears repeated shear load. Cumulative plastic deformation is generated under ultra-high-cycle circulation even if the stress level is lower than the material yield strength. Dislocations on the surface metal continuously proliferate, slip and entangle to form dense dislocation cell structures, resulting in grain distortion and refinement, degradation of surface mechanical properties and reduction of fatigue resistance.

Secondly, surface defects and stress concentration are formed. Friction and wear caused by micro-slip produce microscopic defects such as furrows, pits and delamination on the interface [17]. A large number of iron oxide wear debris is generated and embedded into the contact surface as third-body particles, further aggravating friction wear and surface damage, forming numerous microscopic stress concentration points and providing favorable conditions for micro-crack nucleation.

Finally, ultra-high-cycle micro-crack initiation and propagation take place. Under the coupling action of bending normal stress and shear friction stress, micro-cracks preferentially initiate at microscopic stress concentration points, grain boundaries and non-metallic inclusions [18]. Under ultra-high-cycle conditions, the crack propagation rate is extremely low, and micro-cracks remain in a subcritical propagation state for a long time, gradually growing after billions of cyclic accumulations and finally breaking through the critical size to form macroscopic cracks. Meanwhile, water vapor and oxygen in the atmospheric environment participate in frictional chemical reactions, induce fretting corrosion, accelerate the evolution of microscopic defects and crack propagation, and form mechanical-chemical coupled damage.

3.3. Wear-Crack Competitive Coupling Mechanism

The core coupling mechanism of ultra-high-cycle fretting fatigue is the dynamic competitive effect between fretting wear and fatigue crack initiation, which is the fundamental reason for the large life dispersion and complex damage law of wheel axles under ultra-high-cycle conditions. The two damage behaviors restrict and promote each other, dynamically dominating the damage evolution process in different service stages.

The inhibitory effect of wear is mainly reflected in the peeling and elimination of surface micro-cracks. Under micro-slip action, the interface surface is continuously worn, and the newly initiated micron-scale micro-crack nuclei are peeled off and flattened by wear debris, which effectively eliminates the crack initiation source and prolongs the crack initiation life, serving as a natural protection mechanism for press-fitted structures. The larger the slip amplitude, the more significant the wear inhibition effect, so the complete slip zone is always dominated by wear without crack initiation.

The promoting effect of wear is mainly reflected in the aggravation of stress concentration. Continuous wear destroys the original flatness of the interface, forms a large number of microscopic defects, changes the interface contact stress distribution, increases the local stress concentration coefficient, and creates conditions for micro-crack initiation. At the same time, wear leads to gradual attenuation of interface interference pre-pressure and continuous expansion of slip area, further aggravating fretting fatigue damage [19].

In the ultra-high-cycle circulation process, the two effects compete dynamically: the wear inhibition effect dominates in the early service stage, and crack initiation is effectively suppressed; with the increase of service cycles, surface wear tends to be stable, the stress accumulation effect becomes prominent, the crack promotion effect gradually dominates, and micro-cracks initiate and propagate continuously, eventually leading to fatigue failure. This competitive mechanism is comprehensively regulated by interference, friction coefficient, load amplitude and service cycles, and is also the core difficulty in the research of ultra-high-cycle fretting fatigue mechanism.

4. Domestic and Foreign Research Status

4.1. Experimental Testing and Characterization Technology

Aiming at the fretting fatigue problem of railway press-fitted wheel axles, domestic and foreign scholars have constructed a three-level experimental system of small specimen fretting test, scaled shaft-sleeve test and full-scale wheel-set bench test, and systematically studied fretting damage laws and ultra-high-cycle failure characteristics combined with microscopic characterization technology.

Foreign research started early. Nishioka and Hirakawa took the lead in carrying out rotating bending fretting fatigue tests on railway interference-fit axles, clarified the core characteristics of fretting cracking at the edge of press-fit interfaces, and laid the foundation for the research of fretting fatigue of railway components. In recent years, foreign teams have adopted the staircase method to carry out ultra-high-cycle fretting fatigue tests above 107 cycles. A large number of control tests have confirmed that metal materials have no traditional fatigue limit under fretting conditions, verifying the inevitability of low-stress ultra-high-cycle failure [20]. Meanwhile, quantitative evaluation of multi-source crack initiation is carried out based on the critical distance theory and modified Wöhler curve, and the equivalent stress at the slip boundary is proposed as the core parameter controlling fretting fatigue damage.

Domestic research institutions such as Southwest Jiaotong University, China Academy of Railway Sciences and CRRC have carried out targeted research focusing on the service characteristics of EMU wheel axles. Independently developed rotating bending fretting fatigue test devices are adopted to simulate the actual press-fitting assembly and load conditions of wheel axles, and the influence laws of interference, load amplitude and friction coefficient on interface slip zoning, micro-slip amplitude and damage degree are systematically explored. Based on the cutting detection of decommissioned physical wheel axles, microscopic characterization technologies such as scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD) are used to observe the interface wear morphology, crack morphology, grain distortion and dislocation evolution after ultra-high-cycle service, revealing the initiation and propagation characteristics of multi-source short cracks [21].

Current experimental research still has significant bottlenecks. Firstly, the efficiency of ultra-high-cycle tests is limited. Traditional rotating bending testing machines cannot realize rapid loading of 108-109 cycles, and ultrasonic high-frequency fatigue testing machines are only applicable to smooth small specimens, unable to reproduce the complex contact boundary conditions of press-fit interfaces. Secondly, the scale effect is prominent. The fretting parameters of small specimens and scaled models cannot be completely equivalent to those of physical wheel axles, making it difficult to directly apply test results to engineering life evaluation. Thirdly, in-situ observation of closed interfaces is difficult. The press-fit interface is an internal closed structure, which cannot realize in-situ observation of the whole process of micro-slip evolution and micro-crack initiation under ultra-high cycles, and the dynamic evolution law of early damage is difficult to accurately capture.

4.2. Numerical Simulation and Interface Mechanical Behavior Research

Numerical simulation is a core means to make up for experimental deficiencies and quantify the micro-dynamic behavior of press-fit interfaces. At present, finite element software such as ANSYS and ABAQUS are widely used at home and abroad to construct wheel axle interference-fit simulation models, accurately solve core fretting parameters such as interface contact pressure, tangential shear stress, micro-slip amplitude and slip zone distribution, and analyze the influence laws of structural and load parameters on fretting behavior [22].

Conventional steady-state simulation research is relatively mature, which can accurately reveal the influence of interference, transition fillet, friction coefficient and external load on interface fretting distribution. It has been clarified that optimizing the transition fillet at the wheel seat end can effectively reduce edge stress concentration, narrow the dangerous slip area, and a reasonable interference range can realize the effective balance of wear and fatigue damage.

In recent years, simulation research has gradually developed towards dynamic evolution and multi-scale coupling. On the one hand, Archard wear model and energy-based wear model are introduced to construct an iterative wear simulation framework, which updates the interface geometric morphology through cyclic iteration and simulates the dynamic influence of wear evolution on contact stress field and slip behavior in long-term service, which is closer to the actual service conditions. On the other hand, multi-scale simulation methods are developed. The macroscopic model solves the overall stress-strain field of the wheel axle to provide boundary conditions for the microscopic model, and the microscopic model focuses on the interface surface layer to analyze microscopic damage behaviors such as dislocation evolution and micro-crack nucleation, realizing the linkage analysis of macroscopic mechanical response and microscopic damage mechanism.

Current simulation research has obvious limitations. Most simulation models are constructed based on constant amplitude loads, unable to reproduce the actual service load spectrum of EMUs with random impact and variable amplitude alternating loads, resulting in large deviation from engineering practice. The calculation cost of ultra-high-cycle damage simulation is huge, and the existing computing power cannot realize the full-cycle dynamic simulation above 108 cycles. The wear-crack coupled constitutive model is not perfect, unable to accurately characterize their dynamic competitive evolution process, and the simulation accuracy cannot meet the requirements of ultra-high-cycle life prediction.

4.3. Ultra-High-Cycle Fretting Fatigue Life Prediction Research

Traditional S-N curve fatigue theory and linear cumulative damage criterion are only applicable to medium and low-cycle conventional fatigue, and cannot adapt to the complex damage conditions of fretting coupled ultra-high-cycle fatigue. Domestic and foreign scholars have carried out a large number of modifications and innovative researches on ultra-high-cycle life prediction of press-fitted wheel axle structures, forming three mainstream evaluation methods [23].

The first is the critical plane-based damage parameter method. Relying on fretting damage parameters such as SWT, FSI and MWCM, combined with local stress-strain fields, the fatigue dangerous plane is screened, the local damage degree is quantified, and the micro-crack initiation life is predicted. This method can effectively adapt to multi-axis alternating load conditions and is the mainstream method for fretting fatigue life prediction at present. However, the applicability of damage parameters decreases significantly and the prediction accuracy is greatly reduced in the ultra-high-cycle range above 107 cycles.

The second is the modified theory based on critical distance. Aiming at the problems of stress singularity and large stress gradient at the press-fit interface edge, the critical distance theory is introduced to correct the local stress calculation results, avoid the life prediction deviation caused by stress concentration, and effectively improve the prediction accuracy in the short crack initiation stage. Nevertheless, it fails to consider the influence of ultra-high-cycle wear evolution on damage accumulation and cannot adapt to long-term service conditions.

The third is the modified ultra-high-cycle S-N curve model. By introducing wear influence coefficient and load correction coefficient, the traditional fatigue S-N curve is modified in sections to construct an ultra-high-cycle fretting fatigue life model adapted to 107~109 cycles, making up for the theoretical defect of no fatigue limit in traditional models. However, most model parameters are fitted based on experiments with unclear physical mechanisms and poor universality.

From the perspective of engineering application, the design and verification of EMU wheel axles are still mainly based on the industry standard TB/T 2368, which takes the fatigue strength of 107 cycles as the core verification index. There is no design and evaluation system adapted to ultra-high-cycle fretting fatigue, and the residual life evaluation of in-service wheel axles still relies on macroscopic crack detection inversion, lacking quantitative and accurate ultra-high-cycle damage evaluation methods [24].

4.4. Research on Anti-Fretting Fatigue Protection Technology

To restrain the ultra-high-cycle fretting damage of wheel axle press-fit interfaces and improve the long-term service performance of structures, the industry has formed three mature protection technologies including structural optimization, process control and surface modification, which are continuously upgraded iteratively.

In terms of structural optimization, the transition fillet at the wheel seat end is optimized, the reasonable interference is matched, and the hub structural stiffness is optimized to reduce the edge stress concentration of the interface, regulate the range and amplitude of slip area, weaken the driving force of fretting damage from the mechanical source, and effectively balance the competition relationship between wear and fatigue damage.

In terms of assembly process control, the press-fitting process parameters are strictly standardized, including the matching surface roughness, press-fitting speed and press-fitting force-displacement curve, to ensure the uniformity of interference fit, avoid local stress concentration and poor fitting, and improve the assembly quality and service stability of the interface.

Surface modification strengthening is the core technology to improve ultra-high-cycle fretting fatigue resistance at present. The mainstream processes include ion nitriding, roller strengthening and laser shock strengthening [25]. Stable residual compressive stress is introduced into the wheel seat surface layer through surface strengthening processes to refine surface grains, improve surface hardness, effectively inhibit dislocation accumulation and micro-crack initiation, reduce interface friction coefficient and alleviate fretting wear, which can significantly improve the ultra-high-cycle service life of wheel axles, and has been gradually applied to the manufacturing of new EMU wheel axles and the repair of old wheel axles.

5. Key Problems in Current Research

Comprehensively reviewing the domestic and foreign research status, current research on ultra-high-cycle fretting fatigue of EMU wheel axle press-fitted structures has clarified the basic failure characteristics and macroscopic mechanisms, but there are still many key problems to be broken through in microscopic coupling mechanism, test equivalence, life prediction and engineering application, as follows.

First, the wear-crack competitive coupling mechanism under ultra-high-cycle conditions is unclear. Existing studies have only confirmed the dynamic competition relationship between them, but failed to quantify the inhibition threshold of wear on micro-crack initiation and the promotion mechanism of stress accumulation on crack propagation under ultra-high cycles, unable to accurately describe the dominant damage form in different service stages and load conditions, and the physical model of microscopic coupling evolution has not been established.

Second, the test scale effect and equivalent conversion system are missing. The stress gradient, slip amplitude and constraint conditions of small specimen and scaled tests are quite different from those of physical wheel axles. The existing research has not established a perfect scale similarity criterion, so test data cannot be directly mapped to engineering physical components, resulting in difficult engineering transformation of test results.

Third, the ultra-high-cycle damage accumulation model under random coupled loads is imperfect. Existing studies mostly carry out mechanism analysis and model construction based on constant amplitude alternating loads, ignoring the actual service conditions of EMUs such as wheel-rail impact, variable amplitude load and vibration coupling. The influence mechanism of load sequence effect and impact interaction on damage accumulation is unclear, unable to accurately characterize the damage evolution law in actual service.

Fourth, the accuracy and universality of ultra-high-cycle fretting fatigue life prediction are insufficient. Most existing life models are empirical fitting models with incomplete physical mechanisms, insufficient consideration of ultra-high-cycle short crack propagation and dynamic wear evolution, and large dispersion of prediction results. There is no standardized prediction system adapted to engineering design, life evaluation and operation and maintenance inspection.

Fifth, the early micro-damage detection technology of press-fit interfaces lags behind. Conventional ultrasonic and penetration detection technologies are difficult to identify micron-scale wear and subsurface micro-cracks of press-fit closed interfaces in early ultra-high-cycle damage. The existing nonlinear ultrasonic detection and micro-damage detection technologies have not realized engineering application, unable to support early damage warning and full-life-cycle accurate operation and maintenance of wheel axles.

6. Future Research Prospects

Combined with the safety operation and maintenance requirements of high-speed EMUs and the current research deficiencies, the future research on ultra-high-cycle fretting fatigue of wheel axle press-fitted structures should focus on three major directions of mechanism deepening, technological innovation and engineering implementation, with key research contents as follows.

First, deepen the research on multi-scale coupled damage mechanism. Relying on the ultrasonic ultra-high-cycle fatigue test platform and high-precision microscopic characterization technology, systematically observe the microscopic processes of surface dislocation evolution, grain distortion and inclusion-induced crack initiation of wheel axle materials under 108~109 cycles, quantify the dynamic competition threshold of wear and crack, establish a multi-scale coupled mechanism model of "macro mechanical response-mesoscopic friction wear-micro damage evolution", and improve the theoretical system of ultra-high-cycle fretting fatigue.

Second, construct hierarchical tests and scale equivalence criteria. Improve the three-level test system of "small specimen-scaled shaft sleeve-full-scale wheel set", systematically study the differences of fretting behaviors of components with different scales, establish the scale conversion formula of fretting parameters, damage laws and life parameters, solve the problem of engineering transformation of test data, and provide reliable test support for mechanism research and model verification.

Third, develop ultra-high-cycle life prediction models adapted to random loads. Carry out ultra-high-cycle fretting fatigue tests under variable amplitude and impact coupling conditions based on measured wheel axle load spectra of EMUs, reveal the influence laws of load sequence and impact amplitude on damage accumulation, establish a wear-fatigue coupled damage accumulation model with both physical mechanism and engineering accuracy, form a standardized ultra-high-cycle life evaluation method for wheel axles, and improve the industrial design and verification standards.

Fourth, optimize multi-scale numerical simulation technology. Develop dynamic wear iterative simulation and multi-scale coupled simulation methods, integrate real random load spectra and material microscopic damage constitutive relations, realize the full-process numerical deduction of interface damage evolution under ultra-high cycles, accurately predict dangerous damage areas and life ranges, and provide simulation support for structural optimization and process improvement.

Fifth, promote the research and development of active protection and intelligent detection technology. Optimize the collaborative protection scheme of surface strengthening, structural optimization and assembly technology, develop integrated anti-fretting fatigue protection technology adapted to ultra-high-cycle conditions; break through the accurate early micro-damage detection technology of closed interfaces, develop nonlinear ultrasonic intelligent detection and damage quantitative evaluation system, and realize early damage warning, residual life prediction and full-life-cycle intelligent operation and maintenance of wheel axles.

7. Conclusion

Ultra-high-cycle fretting fatigue of EMU wheel axle press-fitted structures is a complex long-term damage problem coupled by tribology, material mechanics, structural mechanics and environmental chemistry. Its characteristics of no fatigue limit, concealed multi-source crack initiation and wear-crack competitive evolution are different from conventional mechanical fatigue, which is the core bottleneck restricting the long-life and high-reliability service of high-speed wheel axles. Current domestic and foreign research has basically clarified the interface zoning characteristics, macroscopic failure laws and basic damage mechanisms of press-fit structures, and formed a preliminary research system of experiment, simulation, life evaluation and protection technology. However, there are still significant deficiencies in microscopic coupling mechanism, scale equivalent conversion, random load damage accumulation, engineering life evaluation and early detection technology.

Future research should focus on the core scientific problems of ultra-high-cycle fretting fatigue, deepen the research on multi-scale coupling mechanism, construct a life prediction system adapted to actual service conditions, innovate protection and detection technologies, promote the in-depth integration of theoretical research and engineering application, improve the full-chain technical system of independent design, process optimization, life evaluation and safe operation and maintenance of high-speed EMU wheel axles in China, and provide solid theoretical and technical guarantee for the long-term safe and stable operation of high-speed railways.

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