Review of Research on Gear Fatigue Life

Wang Yu
Automotive Engineering
College
Zibo Polytechnic University
Zibo 255300, PR China

Abstract: This paper systematically reviews the research progress on gear fatigue life, focusing on theoretical, simulation, and experimental approaches. Theoretically, mature standards (e.g., ISO 6336) provide foundational guidance for gear strength verification, while advanced models based on damage mechanics and strain-life methods offer deeper insights into bending and contact fatigue mechanisms. Simulation techniques, utilizing finite element analysis and multi-body dynamics, enable precise characterization of stress distribution and crack propagation, facilitating effective fatigue life prediction and design optimization. Experimentally, fatigue test rigs remain indispensable for validating material performance, surface treatments, and lubrication effects, though their application is often limited by time and cost constraints. Moving forward, research trends emphasize the development of efficient multi-field coupling models and the integration of theory, simulation, and testing to enhance prediction accuracy and gear reliability. This review serves as a comprehensive reference for anti-fatigue design and future studies in gear transmission systems.

Keywords:contact fatigue; bending fatigue; life prediction; finite element analysis; fatigue testing

1. INTRODUCTION

Whether it is a traditional fuel vehicle or an electric vehicle, gears are essential components of the transmission system. During operation, gears are subjected to contact pressure, frictional force, meshing impact force, bending stress, and other forces, with complex loading conditions that can lead to fatigue failure, thereby affecting the service life and operational reliability of the transmission system. Although major automotive companies test the components they produce before they leave the factory, accidents still occur frequently. Therefore, the strength and fatigue life of automotive parts remain issues that manufacturers must consider [1].

Fatigue failure is fundamentally different from static strength failure. Static strength failure occurs under a single load, while fatigue failure results from the accumulation of damage after numerous cycles of alternating stress. Compared to static strength failure, fatigue failure can occur when the stress is far below the material's tensile limit. Fatigue fractures are sudden and show no obvious plastic deformation. Fatigue failure usually takes a long time to occur. Besides the material, fatigue failure is also related to the shape of the part and surface processing techniques. The fracture surface of a fatigue failure can be divided into three parts: the instantaneous fracture zone, the fatigue source, and the crack propagation zone [2].

Fatigue can be classified into low-cycle fatigue, high-cycle fatigue, and ultra-high-cycle fatigue based on the number of failure cycles. Low-cycle fatigue refers to the failure of components under high stress within less than 10^4 cycles. High-cycle fatigue occurs within 10^4 to 10^7 cycles. Ultra-high-cycle fatigue involves lower stress levels and failure occurs after more than 10^7 cycles. The fatigue behavior of gears is characterized by a continuous damage process over a high number of cycles, falling within the range of high-cycle fatigue or even ultra-high-cycle fatigue [3].

2. THEORETICAL RESEARCH ON GEAR FATIGUE LIFE

Bending and contact fatigue failure are the main damage forms of gears in vehicle transmission systems. Conducting bending and contact strength checks on gears is an essential process in gear design. The fatigue strength checking methods for gears include ISO 6336, AGMA 2001, DIN 3990, GB/T 3480, etc., and are widely used in engineering [4-5].

Čular et al.[6] based on the strain life method, conducted bending fatigue analysis on carbonized gear steel samples under low-cycle and high-cycle fatigue conditions, and proposed a method to convert axial fatigue data into bending fatigue data by using the Neuber rule and correction factors. Xu Heming et al.[7] constructed a damage constitutive model based on the Lemaitre-Chaboche plastic damage theory to predict the bending fatigue life of gears. Sanchez et al.[8] considered the influence of uneven distribution of contact line load on root bending stress of gears according to the minimum elastic potential energy criterion.

According to the different materials, tooth shapes, and working conditions, gear contact fatigue failure may present different failure modes such as macroscopic pitting, micro-point erosion, and wear. Xu et al.[9] found that micro-point erosion is mainly related to the local contact conditions of the tooth surface, and usually extends about several micrometers in the depth and width directions below the tooth surface. Any material and processing method of the tooth surface can cause micro-point erosion fatigue, and it is most common in grinding and carbonized gears. Liu et al. [10] found that in the wear process, the critical damage position moves from the near surface to the deeper sub-surface, and the failure mode gradually changes from micro-point erosion to pitting. The wear process triggers a competition mechanism between contact fatigue failure between the tooth surface and the sub-surface of the gear. Morales-Espejel et al. [11] found that the wear effect shifts the location of micro-point erosion to the single-tooth meshing area instead of the position with the maximum contact pressure on the tooth surface when not considering wear. Tang Zhonglian et al.[12] explored the influence of roughness on the contact pressure of the tooth

surface, and the research results showed that surface roughness causes stress concentration at the sub-surface of the contact area of the transmission gear. Kissling et al. [13] used the Kisssoft software to study the influence of gear shape on micro-point erosion, and the results showed that optimizing the macroscopic shape of the gear can improve the anti-micro-point erosion ability of the tooth surface. Wang Shuren et al. [14] established a mathematical model for tooth surface fatigue wear calculation applicable to closed gear transmissions and gave the determination methods of each parameter in the calculation model. Gear contact fatigue failure is due to its diverse failure forms and numerous influencing factors, which is a research challenge at home and abroad. In engineering applications, the anti-point erosion ability of gears is generally enhanced by gear shaping [15], increasing the viscosity of lubricating oil [16], and surface hardening treatment.

3. SIMULATION RESEARCH ON GEAR FATIGUE LIFE

In the realm of automotive transmission gears, while theoretical calculations hold guiding importance for their design, they are limited in directly reflecting stress variations and the precise location of maximum stress. With the progressive development and maturation of diverse finite element software, simulation analysis has emerged as an effective approach for predicting the strength and fatigue life of transmission system gears.

Wang Xiaqun et al.[17] employed ANSYS software to explore the impact of the tooth root transition curve on gear stress and strain, thereby offering a theoretical foundation for engineers to make rational choices regarding gear processing methods. Govind et al.[18] utilized the extended finite element method to investigate the variation pattern of time - varying meshing stiffness and the crack propagation behavior of straight gears. Zhang Jiancheng et al.[19] established a virtual prototype and operated it on a digital graded road surface to acquire the full - life fatigue load spectrum essential for gear fatigue analysis. Chao Lin et al.[20] computed the gear load spectrum in ADAMS, simulated the gear bending stress in ANSYS Workbench, and determined the bending fatigue life of the surface gear by integrating the load spectrum and stress values in Ncode Designlife. Liu Xinbo et al. [21] approximated the dynamic meshing process of gears as static mechanical analyses at different meshing positions and calculated the crack propagation paths, stress intensity factors, and remaining fatigue life of gears with initial cracks at various meshing positions. Glode et al. [22] separately carried out finite element simulations of the crack initiation and propagation processes. They determined the stress cycle number for fatigue crack initiation using the strain - life method and simulated the fatigue crack propagation process via the Paris equation. Gao Donghai et al. [23] discovered that assembly issues can lead to abnormal wear on the gear end face, causing a reduction in gear meshing stiffness and a shortening of the gear's fatigue life.

Wei Wang et al. [24] utilized Python coding within ABAQUS to calculate the multi - axis equivalent stress of Dang Van for gears. Their findings indicated that as the depth of the hardened layer increases and the surface hardness decreases, the risk of deep peeling contact fatigue failure of the gear diminishes. Conversely, with an increase in surface hardness, the risk of pitting contact fatigue failure decreases. Haifeng He et al. [25] calculated the stress response during the cyclic loading process of gears in the subroutine UMAT of ABAQUS. The results demonstrated that as the loading cycle increases, the maximum damage migrates towards the surface

yet remains within the subsurface area, and the first fatigue crack initiates at the subsurface near the node. Zhao Han et al. [26] conducted simulation modeling using MATLAB/Simulink software to obtain the contact stress fatigue load spectrum of gearbox gears under UDDS instantaneous road conditions and proposed a novel stress counting method. Aslantas et al. [27] established a simulation model for predicting the point wear life of gears under rolling conditions and forecasted the angle and rate of point wear crack propagation. Sheng et al. [28] developed a numerical analysis model for the micro - pitting of straight gears and predicted the micro - pitting life considering lubrication and tooth surface roughness. Liu et al. [29] explored the influence of gear surface coating parameters on contact characteristics. The results showed that the mechanical properties of the coating had no marked impact on the orthogonal shear stress distribution but significantly affected the Von Mises stress distribution. Under a specific coating thickness, the maximum Von Mises stress generated by the soft - coated gear was lower than that of the hard - coated gear under identical working conditions.

4. EXPERIMENTAL RESEARCH ON GEAR FATIGUE LIFE

The experimental method simulates the actual operating conditions of gears using fatigue test benches, providing important guidance for studying the load-bearing capacity and lifespan of gears. Chen Yong et al. [30] investigated the effect of coatings on the fatigue life of automotive transmission gears through fatigue tests, verifying that manganese phosphate coatings can effectively enhance the fatigue life of gears. Chang et al. [31] compared wear particles in oil with images of tooth surface pitting and found that the concentration of wear particles showed a similar growth trend to the pitting area, albeit with a certain delay. Wang Daoyong [32] used the Locati rapid determination method for fatigue limits to conduct comparative fatigue tests on gears subjected to vibrational finishing and those without. The test results demonstrated that vibrational finishing technology improves tooth surface smoothness and extends the fatigue life of gears. Oila et al. [33] studied the formation and propagation of micro-pitting, finding that the slide-to-roll ratio and speed are the main factors contributing to the propagation of micro-pitting, while load is the primary factor causing its formation. Hohn et al. [34] showed that an increase in lubricating oil temperature reduces oil film thickness, promoting gear wear and pitting. However, the increase in lubricating oil temperature also enhances the activity of extreme pressure additives in the oil, thereby improving the gear's resistance to scuffing.

The experimental method is a traditional fatigue testing approach that can accurately reflect the actual working conditions of gears. However, its application is constrained by the long testing cycles and high costs involved. Consequently, the experimental method is typically employed as a validation tool for simulation and theoretical calculations.

5. CONCLUSION

Based on the review of the current research status on gear fatigue life, the following conclusions can be drawn:

Theoretical research has established mature verification standards and has deepened the understanding of the microscopic mechanisms of bending and contact fatigue, laying a solid foundation for life prediction.

Simulation has emerged as a core analytical approach, capable of precisely characterizing the stress state and damage

processes in gears, thereby enabling effective fatigue life prediction and optimized design.

Experimental research remains an indispensable validation step, offering the highest credibility in assessing actual performance. However, its high costs and extended durations necessitate closer integration with simulation and theoretical methods to form a complementary framework.

Future research on gear fatigue life will likely focus on developing efficient and accurate multi-field coupled prediction models, while deepening the integrated "theory-simulation-experimentation" research system to achieve comprehensive enhancement of gear reliability.

6. REFERENCES

[1] Li Haipeng. Dynamic Characteristic Analysis and Fatigue Life Study of a Transmission Gear [D]. Nanjing University of Science and Technology, 2017.

[2] Li Zhongyi. Torsional Vibration Control of Drive Train in Doubly-Fed Wind Turbine and Fatigue Life Prediction of High-Speed Side Gear Tooth Root [D]. Shihezi University, 2021.

[3] Yao Weixing. Structural Fatigue Life Analysis [M]. Beijing: Science Press, 2020.

[4] Khan M A, Cooper D, Starr A. BS-ISO helical gear fatigue life estimation and wear quantitative feature analysis[J]. Strain, 2009, 45(4): 358-363.

[5] Zhao L, Frazer R C, Shaw B. Comparative study of stress analysis of gears with different helix angle using the ISO 6336 standard and tooth contact analysis methods[J]. Proceedings of the Institution of Mechanical Engineers, 2016, 230(7-8): 1350-1358.

[6] Čular I, Vučković K, Žeželj D, et al. Analytical approach for low and high cycle bending fatigue life prediction of carburized gear steel specimens[J]. Engineering Failure Analysis, 2020, 108: 104328.

[7] Xu Heming, Huang Zaixing, Qiang Lei, et al. A Gear Fatigue Model Based on Damage Constitutive Theory [J]. Journal of Mechanical Strength, 2017, 39(02): 417-422.

[8] Sanchez M B, Pedrero J I, Pleguezuelos M. Critical stress and load conditions for bending calculations of involute spur and helical gears[J]. International Journal of Fatigue, 2013, 48: 28-38.

[9] Xu X, Lai J, Lohmann C, et al. A model to predict initiation and propagation of micro-pitting on tooth flanks of spur gears[J]. International Journal of Fatigue, 2019, 122: 106-115.

[10] Liu H L, Liu H J, Zhu C, et al. Study on gear contact fatigue failure competition mechanism considering tooth wear evolution[J]. Tribology International, 2020, 147: 106277.

[11] Morales-Espejel G E, Rycerz P, Kadiric A. Prediction of micropitting damage in gear teeth contacts considering the concurrent effects of surface fatigue and mild wear[J]. Wear, 2018, 398: 99-115.

[12] Tang Zhonglian, Qi Xiumei, Gao Chuankuan. Influence of Tooth Surface Roughness on Contact Fatigue Stress in Gear Transmission [J]. Lubrication Engineering, 2011, 36(04): 53-57.

[13] Kissling U. The application of the first international calculation method for micropitting[J]. Gear Technology, 2012: 54-60.

[14] Wang Shuren, Yan Yutao, Yin Weili, et al. A Computational Model for Frictional Fatigue Wear in Gear Meshing [J]. Journal of Northeastern University (Natural Science), 2008(08): 1164-1167.

[15] Weber C, Tobie T, Stahl K. Investigation on the flank surface durability of gears with increased pressure angle[J]. Forschung im Ingenieurwesen, 2017, 81(2): 207-213.

[16] Winter H, Weiss T. Some factors influencing the pitting, micro-pitting (frosted areas) and slow speed wear of surface hardened gears[J]. Journal of Mechanical Design, 1981, 103(2): 499-505.

[17] Wang Xiaoqun, Huo Dongju. Study on the Influence of Tooth Root Transition Curve on Gear Bending Fatigue Strength [J]. Machinery Design & Manufacture, 2008(08): 114-116.

[18] Govind V J, Sachin K, Kumar K P. Crack growth modeling in spur gear tooth and its effect on mesh stiffness using extended finite element method[J]. Engineering Failure Analysis, 2018, 94: 109-120.

[19] Zhang Jiancheng, Zhang Qingxia, Mao Zhiyong. Gear Fatigue Life Analysis Based on Driving Simulation Tests [J]. China Mechanical Engineering, 2014, 25(8): 1001-1006.

[20] Lin C, Li P, Liu W. Analysis and calculation of bending fatigue life of curve-face gear[J]. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2020, 42(1): 1-11.

[21] Liu Xinbo, Zeng Xiaosong, Liu Yong. Prediction and Analysis of Bending Fatigue Crack Propagation Behavior in Spur Gears [J]. Journal of Mechanical Transmission, 2016, 40(09): 179-183.

[22] Glode S, Raml M, Kramberger J. A computational model for determination of service life of gears[J]. International Journal of Fatigue, 2002, 24(10): 1013-1020.

[23] Gao Donghai. Failure Analysis of Tooth Breakage in a Transmission Gear [J]. Journal of Mechanical Transmission, 2020, 44(05): 139-145.

[24] Wang W, Liu H, Zhu C, et al. Evaluation of contact fatigue risk of a carburized gear considering gradients of mechanical properties[J]. Friction, 2020, 8(06): 1039-1050.

[25] He H, Liu H, Zhu C, et al. Study on the gear fatigue behavior considering the effect of residual stress based on the continuum damage approach[J]. Engineering Failure Analysis, 2019, 104: 531-544.

[26] Zhao Han, Huang Qingqing, Huang Kang, et al. Study on Contact Fatigue Life of Pure Electric Vehicle Two-Speed Transmission Gear [J]. Journal of Mechanical Transmission, 2016, 40(08): 6-10.

[27] Aslantas K, Tasgetiren S. A study of spur gear pitting formation and life prediction[J]. Wear, 2004, 11(257): 1167-1175.

[28] Sheng L, Ahmet K. A physics-based model to predict micro-pitting lives of lubricated point contacts [J]. International Journal of Fatigue, 2013, 47(2): 205-215.

[29] Liu H J, Liu H L, Zhu C, et al. Tribological behavior of coated spur gear pairs with tooth surface roughness[J]. Friction, 2019, 7(02): 117-128+202.

[30] Chen Yong, Zhou Huidong, Zang Libin, et al. Experimental Study on Fatigue Performance and Contact Strength of Surface-Coated Gears in Automotive Transmissions [J]. Journal of Mechanical Transmission, 2020, 44(6): 18-24.

[31] Chang H, Borghesani P, Peng Z. Investigation on the relationship between macropits and wear particles in a gear fatigue process[J]. Wear, 2021, 484-485: 203724.

[32] Wang Daoyong, Wang Tie, Zhang Ruiliang, et al. Comparative Experimental Study on Contact Fatigue Life of Vibration Finished Gears [J]. Journal of Mechanical Transmission, 2017, 41(1): 74-77.

[33] Oila A, Bull S J. Assessment of the factors influencing micropitting in rolling/sliding contacts[J]. Wear, 2005, 258(10): 1510-1524.

[34] Hohn B R, Michaelis K. Influence of oil temperature on gear fatigue[J]. Tribology International, 2004: 103-109.