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Study on Wear Characteristics Evolution of Helical Gear with Linear Initial Defect

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Keywords： helical gear, linear initial defect, wear forms, surface wear scars.

ABSTRACT

For wind power, ships, and other fields that require machines to work under harsh working conditions, the initial defects of gears greatly affect the working performance of these machines. The influence of linear initial defects on the evolution of wear characteristics of helical gears was studied. The laser marking device was used to process the linear initial defect along the tooth width direction, and the gear without the initial defect was used for comparison. The number and state of wear particles in oil samples were analyzed by particle counter and ferrography, and the wear condition of the gear surface was observed by scanning electron microscope. This study provides a reference for the evaluation of gear wear under harsh working conditions, it can be concluded that the linear initial defect changed the meshing state of the gear tooth, the normal wear life of the gear is shortened by about 45%, and the wear rate in the stable wear stage is increased by about 56%, a great deal of pitting corrosion and plastic flow on the tooth surface occurred in the pitch circle position of the defective gear. In addition, the lubrication condition deteriorated in the later period caused by lubricating oil pollution and the hard particles falling off the gearbox bearings entered the meshing surface and the emerged crack, which further accelerated the wear process of the gear.

INTRODUCTION

As a very important transmission mode, gear transmission has the advantages of high efficiency and strong reliability, which is widely used in the research of mechanical equipment (Kim S, et al., 2015). At the same time, gear is prone to failure forms such as tooth surface wear and tooth surface pitting in the transmission process. These failure forms will further increase the damage to the gear tooth, and even cause tooth broken. Therefore, the requirements of gear transmission in the environment are more stringent than those of belt transmission and chain transmission. However, gears often have inevitable defects due to process problems in the machining process (Wu T, et al., 2019; Bogdevičius P, et al., 2020), and gears may have tooth surface scratches and other wear during the assembly process. These defects will gradually expand with gear transmission process, and further aggravate the wear of the tooth surface. The crack at the root of the tooth can reduce the time-varying meshing stiffness of the gear, thereby accelerating the tooth fracture process (Yu W, et al., 2015; Yang L, et al., 2021). Research shows that the linear tooth surface scratch is one of the most common initial defects of gears (Xiao M, et al., 2021; Nguyen C.D, et al., 2021). For large equipment gears in the field of wind power and ship, the working conditions of high speed and heavy load aggravate the wear rate of gears and magnify the initial defects on the gear surface. Unexpected gear faults caused by initial defects may cause significant economic losses (Ghorbel A, et al., 2019). In order to explore the influence of initial defects on gear wear life under harsh working conditions, it is necessary to study the wear characteristics of gear under linear initial defects.

In recent years, with the rapid development of material technology, polymer gears have gradually attracted the attention of researchers (Kuo C, et al., 2021), but they have problems such as low bearing capacity and poor manufacturing accuracy (Urbas U, et al., 2022), and temperature has a great influence on their working performance (Trobentar B, et al., 2022). In the condition of high speed and heavy load, metal gears are more widely used. The lubricating oil film plays an important role in the contact of the gear, and insufficient lubrication will lead to a large amount of wear between the gear teeth, which will eventually cause the whole system failure (Sharma V, et al., 2020). The gearbox can isolate the external

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environment from the internal gear transmission process, which greatly reduces the external interference to the transmission process (Wu W, et al., 2020). At the same time, the gearbox can store a large amount of lubricating oil, which is convenient for the research and monitoring of gear wear state by wear particle analysis. Therefore, it has been widely used.

In the field of mechanical engineering, the research on faults caused by gear defects through gearbox has always been a research hotspot. Before this paper, many scholars studied the gearbox faults. Nguyen et al. (Nguyen C.D., et al., 2021) proposed a new gearbox fault-sensitive identification system, which classified the types of faulty gear defects by analyzing the vibration characteristics of the gearbox. Yang et al. (Yang L, et al., 2021) studied the influence of tooth root crack defects on meshing stiffness and dynamic response and proposed an improved calculation model for meshing stiffness of cracked gears. Yiqing et al. (Yang Y, et al., 2019) designed a planetary gearbox fault diagnosis system based on Labview, which can accurately identify the characteristic frequency of gear faults, and proved the effectiveness of the system. However, most of them focus on the wear of gears under normal working conditions, without considering the gear wear condition under harsh working conditions. Zhu et al. (Zhu C, et al., 2014; Zhu C, et al., 2015) studied the gearbox and other components in the transmission system of a megawatt wind turbine, but they did not consider the impact of gear defects on the experiment.

The tooth profile has a crucial influence on the wear performance of the gear. Helical gears have the characteristics of smooth meshing, high bearing capacity, and low noise, therefore, helical gears were selected for the initial defect experiment (Jammal A, et al., 2016; Popovich A.G., et al., 2020; Hu X, et al., 2020). The wear characteristics of gear with linear initial defects were studied through the self-built gear performance test bench. Wear particles in the lubricating oil extracted at different time nodes were analyzed by particle counter and analytical ferrography, then the wear characteristics of the tooth surface of the linear initial defective gear after experiment, were analyzed by scanning electron microscope (SEM), and the pollutants in the cracks were analyzed by elemental analysis, which provided an important basis for diagnosing the initial defects of largely closed gear transmission system.

Gear test design

Gear pretreatment

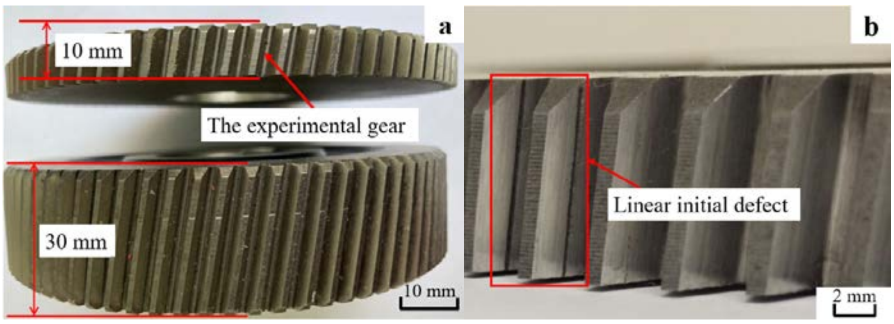
In order to make the experiment better fit the actual working condition of gear, the helical gear selected in this experiment was made of 45# steel with hardness of HBS219. Gear parameters are shown in Table 1. In order to shorten the experimental period, the original 30 mm thick gear was processed by Wire Electrical Discharge Machining, and the test gear with 10 mm tooth width was obtained, as shown in Fig. 1a. In order to avoid deformation and internal stress of gear teeth, the Femtosecond Laser (the working parameters are shown in Table 2) was used to carry out laser marking on the surface of gear teeth near the tooth root along the tooth width direction. A linear initial defect with depth of 0.01 mm and width of 0.25 mm was created, as shown in Fig. 1b.

Table 1. Basic parameters of gears

Name	Number of teeth	Modulus	Tooth width (mm)	Pressure angle	Surface roughness (μm)
Driving wheel	21	1.5	10	20°	2
Driven wheel	82	1.5	10	20°	3

Table 2. Working parameters of Femtosecond Laser

Name	Model	Pulse width (ps)	Frequency (MHz)	Speed (mm/s)	Power (W)
Industrial femtosecond laser	PicoYL-vary	2000	0.800	500	600



(a) Gear wire cutting processing (b) Gear laser marking processing

Fig. 1. Linear initial defective gear

Test bench experimental parameters

The gear test rig with closed-loop power transmission systems are widely used for gear testing (Mara S, et al., 2021). As shown in Fig. 2, the test gearbox was equipped with linear initial defective gear, and the auxiliary gearbox was all normal gear. The test gearbox and the auxiliary gearbox were connected by the elastic torsion shaft and the rigid shaft with the loading flange. When the loading device rotates at a certain angle, the two half couplings of the loading flange respectively transmit the generated torque to the directly connected rigid shaft, and the two opposite action torques are transferred to the elastic shaft through the gears on both sides, resulting in the elastic deformation of the elastic shaft. It can be known from the loading principle that the upper limit of the constant load of the test system is closely related to the torsional strength and torsional stiffness of the elastic shaft material. When a large static load is needed in the experiment, the static load with a different upper limits can be achieved simply by changing the elastic shaft. The three-phase asynchronous motor with model of YE2-112M-4 was selected as the driving device, and the rigid shaft was connected through the transmission belt. The control panel was used to adjust the speed of the motor and record the experimental time. In this experiment, the loading method of forward loading was adopted, and the motor speed was set to 1200 r/min.

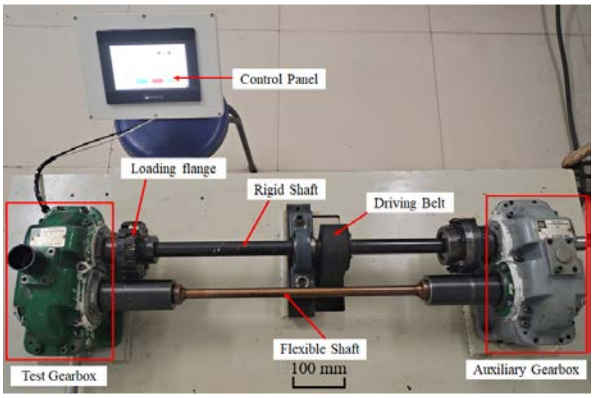


Fig. 2. Experimental platform

The loading flange was used to adjust the loaded torque, which was loaded by the torque wrench, so that the torque was applied to the test gear through the flexible shaft. One loading half coupling has 18 pinholes, and the other half coupling has 16 pinholes. When the two loading half couplings rotate relative to each other by 2.5°, two pairs of hinge holes can be aligned and fixed by hinge hole bolts, as shown in Fig. 3, and then the loading force will be applied on the test gear.

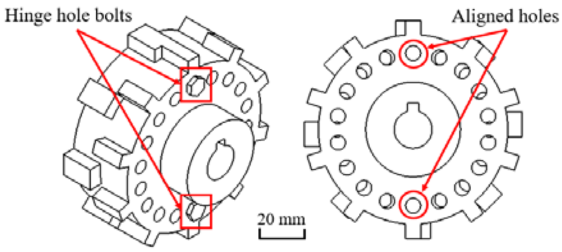


Fig. 3. Loading flange

In order to speed up the process of gear wear and shorten the experiment period, the calculated stress generated by the applied load should be close to the allowable stress of contact fatigue of the gear. The calculated stress of gear contact fatigue strength is shown in Eq. 1.

$$\sigma_H = Z_{BD} Z_H Z_E Z_\varepsilon Z_\beta \sqrt{\frac{F_t}{db}\left(\frac{u}{u+1}\right) K_A K_V K_{H\beta} K_{H\alpha}} \quad (1)$$

where Z_{BD} is the midpoint region coefficient; Z_H is the node region coefficient; Z_E is the elastic coefficient; Z_ε is the coefficient of contact ratio; Z_β is the helix angle coefficient; F_t is the twisting force of gear; d is the gear pitch diameter; b is the tooth width; u is the transmission ratio; K_A is the use coefficient; K_v is the dynamic load factor; $K_{H\beta}$ is the longitudinal load distribution; $K_{H\alpha}$ is the coefficient of load distribution among gear teeth. Relevant parameters can be obtained by calculating and consulting the mechanical design manual.

The calculated stress generated by the applied load can be obtained in Eq. 2 (Zhang G.L., et al., 2015).

$$T = \frac{\left([\sigma_H]/355\right)^2 uba^2}{(u+1)^3 K_A K_V K_{H\beta} K_{H\alpha}} \quad (2)$$

where a is the center distance of gear.

The relationship between the loading torque M and its rotation angle n is shown in Eq. 3.

$$M = 15.18246n - 14.72982 \quad (3)$$

where n is the rotation angle of loading flange; M is the applied torque and the unit is N·m.

According to the calculation results, the load was set as 61.2 N·m, which means the relative rotation of the two loaded half couplings was 5°.

Oil sample processing

Effective lubricating oil is indispensable to the normal operation of the gear. At the same time, the lubricating oil sample in the gearbox contains a lot of wear information, which is often used to analyze the wear state of the gear (Montonen J, et al., 2019; Ghosh G.K., et al., 2021). In order to simulate the real harsh working conditions, shorten the experimental period and accelerate the test process, 32# Caltex White Oil Pharma with few additives was used for lubrication in this experiment, which could not only accelerate the wear process of the gear, but also avoid severe wear in a short time (Yuan W, et al., 2020). The total amount of lubricating oil added to each gearbox was 300 ml. In order to ensure that the wear particles were evenly distributed in the lubricating oil sample, a circulating peristaltic pump was used to continuously pump the lubricating oil from the bottom of the gearbox to the test gear, stop for 5 minutes every 60 minutes, and sample 20 ml lubricating oil from the test gearbox. After sampling, add 20 ml new lubricating oil to ensure the total amount of lubricating oil in the gearbox was basically unchanged. Figure 4 shows the process of oil sample analysis.

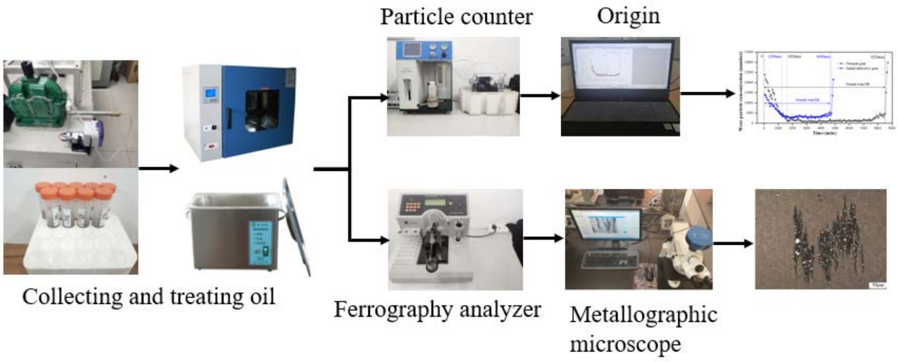


Fig. 4. Oil sample analysis process

Experiments explored the evolution mechanism of gear wear by combining quantitative analysis of wear particles with ferrography analysis technology. First, the lubricating oil sampled from the test gearbox was pretreated, and the collected oil samples were heated by a blast drying oven. The temperature of the oil sample was set 65 °C, and the oil sample was adequately shaken to ensure that the wear particles were evenly distributed in the oil. Then the ultrasonic cleaning machine was used to remove the bubbles generated by vibration in the oil sample, 7 ml was extracted from the oil sample for ferrography analysis, and the remaining oil samples used the particle counter to detect the number of wear particles. The particle counter uses the principle of light-blocking method to measure the number of abrasive particles with different particle sizes in the oil sample. Before the detection, use petroleum ether to flush the particle counter detection system, and pump petroleum ether through the self-priming pump to clean the previous detection oil left in the equipment, so as to avoid the residual oil interfering with the detection results. At the end of the test, the abnormal vibration and noise increased significantly, accompanied by periodic impact sound, which indicates that the test gear has been damaged. At this time, observe the gear state from the gearbox observation port. After the gear tooth was broken, the test was stopped and the last sampling was conducted.

Result Analysis

Analysis of wear particle concentration

The pretreated oil samples were processed and analyzed by YJS-170 particle counter, and the number of abrasive particles in different periods was obtained. The wear life of gear is related to its wear threshold. When the number of abrasive particles in the oil sample reaches the ultimate wear value, it is determined as the wear threshold value of the gear, as shown in Eq. 4.

$$W \le W_{1t} + W_{2t} \tag{4}$$

where, W_{1t} and W_{2t} represent the total wear amount of the driving gear and the driven gear, and W represents the threshold of the gear wear. When the total wear amount of the gear in the oil is greater than the wear threshold, it is considered that the gear is failure caused by wear. Studies have shown that the wear particles with particle size above 15 μm can better characterize the change of fatigue wear (Hong W, et al., 2018). In this study, wear particles with particle size between 15 μm and 25 μm were selected to characterize the change of fatigue wear. In order to further explore the influence of linear initial defects on the wear characteristics of helical gears, the test two was carried out with 10 mm thick non-initial defect gear under the same speed, load, and lubrication conditions, and the oil samples collected from the test two were processed and analyzed. The two groups of data were compared, as shown in Fig. 5.

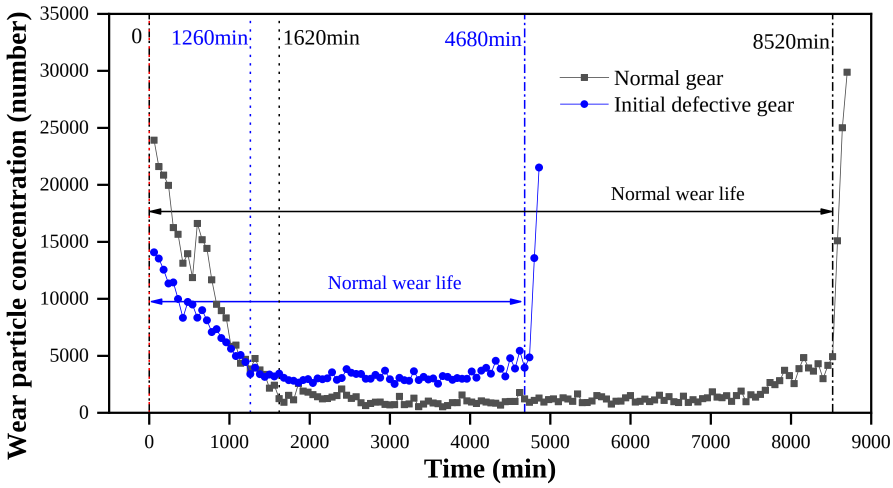


Fig. 5. Comparison of wear particle changes

It can be seen from Fig. 5 that both the linear initial defective gear wear test and the normal gear wear test have a U-shaped distribution in the number of abrasive particles, indicating that the test one and the test two have the same wear trend. In the running-in stage, wear rate was large, the number of abrasive particles were large and gradually decreased, but the noise of the test one was relatively large. The wear experiment of the linear initial defective gear entered the steady wear stage at about 1260 min. At this time, the noise of the test one became smaller, and the number of abrasive particles stabilized at the end of the running-in stage, while the normal gear wear test entered the steady wear stage at about 1620 min, and the number of abrasive particles were significantly less than that of the linear initial defective gear. When the experiment was carried out for about 4680 min, the wear experiment of linear initial defective gear entered a severe wear stage. At this time, the number of abrasive particles increased sharply. However, the normal gear test enters the severe wear stage when it was about 8520 min.

The normal wear life of the gear refers to the life in the running-in stage and the steady wear stage. It can be obtained from Fig. 5 that the normal wear life of the linear initial defect gear is 4680 min, but the normal gear is 8520 min. Compared with the normal gear, the normal wear life of the gear with linear initial defects is shortened by about 45%.

In order to explore the influence of linear initial defects on the normal wear life of gears, the number of wear particles in the running-in stage and the steady wear stage were statistically analyzed, and normal gears were used for comparison, as shown in Fig. 6, In the running-in stage, the number of abrasive particles in the lubricant sample of the linear initial defective gear was less than that of the normal gear, indicating that the linear initial defect has the function of storing oil pollution at the early stage of the experiment. In the steady wear stage, the working time of the linear initial defect gear was much shorter than that of the normal gear, but the number of abrasive particles was slightly more, which indicates that the linear initial defects greatly aggravate the wear of the gear in the steady wear stage. In this experiment, the test one have approximately 190443 abrasive grains in the stable phase, and the test two have approximately 168,133 abrasive grains. Compared with the normal gear, the wear rate of the gear with linear initial defects increased by about 56% in the steady wear stage. In the severe wear stage, there was no significant to discuss the number of wear particles at this stage, because the teeth of both the normal gear and the gear with linear initial defects break quickly. It can be seen that the initial linear defect can change the meshing state of the gear teeth, but seriously damages the working life of the gear and makes the gear more prone to tooth breakage.

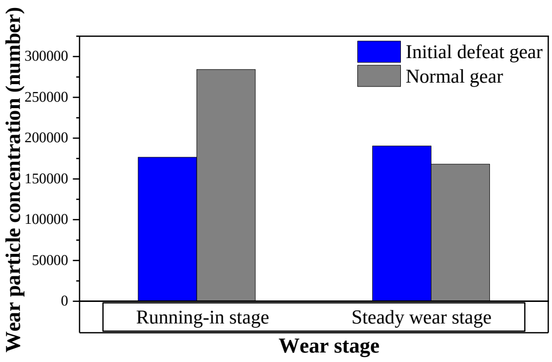


Fig. 6. Comparison of the number of abrasive particles in different wear stages

Ferrography analysis of wear particles

Ferrography technology is a technology to infer the health state of the machine by detecting the characteristics of wear particles, which is widely used in the wear debris of gearbox oil samples (Xi W, et al., 2018; Gholap A.B., et al., 2020). The morphology of wear particles observed by ferrography analysis can effectively reflect the wear degree in different characteristic periods. In this experiment, YTF-5 single link analysis ferrography instrument was used to make ferrographs of oil samples collected in various periods, which were observed by scanning electron microscopy and analyzed to obtain the wear particle characteristics of linear initial defect gear in different wear stages.

Figures 7-9 respectively show the comparison of the ferrographic images of the normal gear and the linear initial defective gear at the representative key time points. Among them, Fig. 7(a), Fig. 8(a) and Fig. 9(a) are typical ferrogram images of normal gears in different periods, and Fig. 7(b), Fig. 8(b) and Fig. 9(b) are typical ferrogram images of linear gears with initial defects in different periods. Figure 7 compares the ferrogram of the normal gear and the linear initial defective gear at 180 min. It can be seen from the figure that the width of the abrasive chain was coarse and the abrasive grain was large, but the oil pollution in the ferrograph of the gear with linear initial defect was less.

Due to the large time difference between the normal gear and the linear initial defective gear in the stable wear stage, in order to ensure its comparability, Fig. 8 selects the ferrography of the oil sample produced by the normal gear at 4800 min and the ferrography of the oil sample produced by the linear initial defective gear at 2400 min for comparison. At this time, the linear initial defect was covered by the oil pollution carrying the wear particles. The width of the abrasive chain was changed from coarse to fine, and the number of large abrasive particles was significantly reduced compared with that in the running-in wear stage. The wear condition was roughly the same as that of the normal gear.

A lot of huge abrasive particles will be produced when the gear tooth is broken, which seriously affects the analysis and processing of ferrography images. Therefore, the oil samples collected last time before tooth fracture were used for analysis. In other words, the ferrography of oil samples produced by normal gear at 8460 min was compared with that of oil samples produced by linear initial defective gear at 3180 min, as shown in Fig. 9. At this time, the width of the abrasive chain increases, the number of large abrasive particles increases, and the number of abrasive particles in the linear initial defective gear was far more than that of the normal gear.

Fig. 7. Comparison diagram of ferrography analysis in running-in stage
(a) normal gear, (b) gear with defect

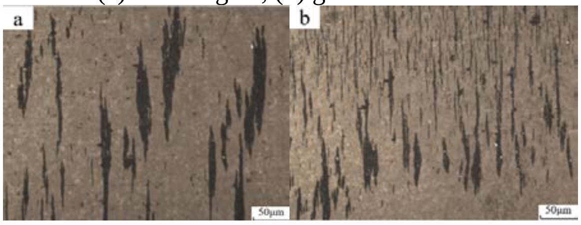


Fig. 8. Comparison diagram of ferrography analysis in steady wear stage
(a) normal gear, (b) gear with defect

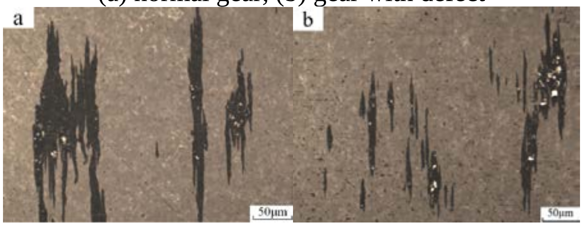


Fig. 9. Comparison diagram of ferrography analysis in severe wear stage
(a) normal gear, (b) gear with defect

SEM analysis of tooth surface

SEM can qualitatively characterize the surface morphology and provide more abundant wear information (Yan Y, et al., 2020). In order to further explore the influence of linear initial defects on the wear mechanism of the gear surface, it is necessary to conduct SEM microscopic study on the tooth surface of gear with linear initial defects.

Figure 10 shows the SEM image near the tooth root of the test gear. The tooth root bears the maximum bending stress. When the alternating stress exceeds the bending fatigue limit of the material and continues to repeat, fatigue fracture occurs on the side of the tooth root tensile, forming cracks and crushing, while storing a large number of pollutants and hard particles. Figure 11 shows the pitch circle position of the linear initial defective gear. The oil sludge was concentrated here through the extrusion of the meshing gear tooth, forming a large number of furrows. Due to good lubrication, the development of abrasive wear on tooth surface was faster than that of fatigue wear. Under the action of shear stress and friction force, pitting corrosion and plastic flow on tooth and tooth surface occur.

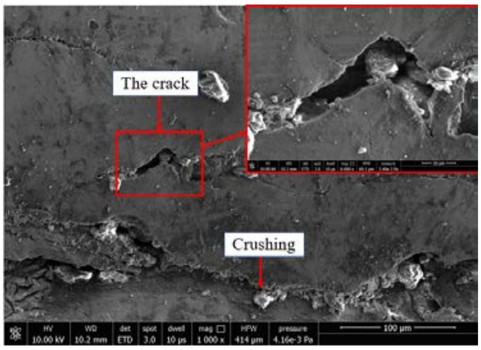


Fig. 10. SEM images of tooth root position of linear

initial defective gear

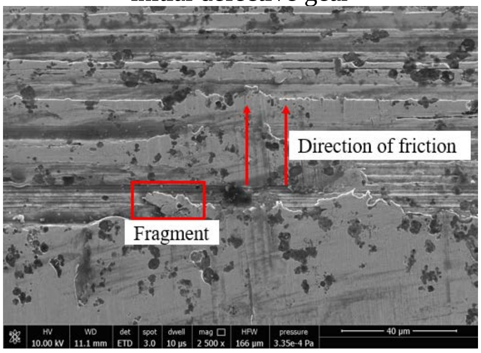


Fig. 11. SEM image of the pitch circle of the linear initial defective gear

In order to explore the influence of the contaminants in the crack on the wear characteristics of the gear, the element analysis of the contaminants in the linear initial defect crack was carried out, and the energy spectrum was obtained, as shown in Fig. 12. It can be seen from the polymer energy spectrum that the main components of pollutants were oil pollution (O) produced by the failed lubricating oil and gear wear particles (Fe). In addition, the elements with high content are Cr and Mn, which were analyzed as the wear of bearing material (GCr15SiMn). The hard abrasive particles generated by the wear of gears and bearings enter the lubricating oil, which aggravates the tooth surface wear and tooth damage, and then generates more hard abrasive particles, thus forming a vicious circle and eventually leading to tooth fracture. Gears with linear initial defects will fatigue earlier, thus accelerating the process of tooth fracture.

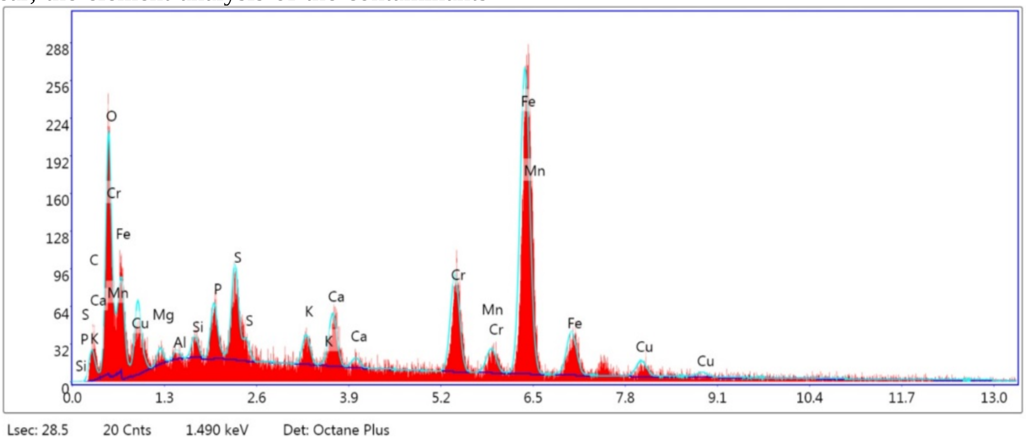


Fig. 12. Energy spectrum analysis of gear pollution polymer

CONCLUSIONS

To reveal the influence of linear initial defects on the normal wear life of gear under harsh working conditions such as high speed and heavy load, the wear characteristics evolution mechanism of the gear with linear initial defects was studied through the tribological experiment. The main results obtained are summarized as follows.

1. In the running-in stage, the linear initial defect of gears can store certain oil pollution and wear particles, thereby reducing the concentration of abrasive particles in the lubricating oil. At the same time, the initial defect also causes great damage to the gear, the normal wear life of gear is shortened seriously and the wear rate of gear in the stable wear stage is greatly increased.
2. According to the comparison diagram of gear wear ferrospectrum analysis and tooth surface SEM analysis, it can be seen that the gear with linear initial defects will suffer early fatigue wear, which changes the direction of sliding velocity of abrasive particles, increases compressive stress, and then pitting and plastic deformation of tooth surface occur. The produced wear particles enter the meshing surface, creating a vicious cycle that accelerates the failure of the gear transmission mechanism.
3. When the lubrication is poor, the hard particles generated by the bearing damage enter the meshing surface and cracks, and accelerate the wear of the gear transmission structure. Therefore, it is necessary to monitor the gear wear state in bad working conditions in time, judge the remaining wear life of the gear, and avoid accidents caused by gear damage.
4. The research method used in this paper has strong universality, which can be used to study the wear characteristics of different types of gears in the gearbox under different working conditions in the future. After the wear particle number change graph is established, it is easy to analyze the wear state of this type of gear in different wear periods. Furthermore, it is also possible to digitize the parameters such as the boundary and area of the wear particles, and the neural network model of gear wear detection is established to identify the wear state of gear according to the wear particle type.

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REFERENCES

Bogdevičius, P., Bogdevičius, M., Prentkovskis, O., *Research on the Rotation Vibration in the Transmission with Gear Box Defects*, Transportation Science and Technology, Springer International Publishing, Cham, (2020).

Ghosh, G.K., Kotia, A., Kumar, N., Ghosh, S.K., "Performance Evaluation of Graphene-Gear Oil Nanolubricants in Rayleigh Step Bearing," *Advances in Metrology and Measurement of Engineering Surfaces*., pp.109-118 (2021).

Ghorbel, A., Abdennadher, M., Walha, L., Zghal, B., Haddar, M., "Modal Analysis of the Clutch Single Spur Gear Stage System with Eccentricity Defect," *Rotating Machinery and Signal Processing*., pp.87-95 (2019).

Gholap, A.B., Jaybhaye, M.D., "Condition Based Maintenance of Gearbox Using Ferrographical Analysis," *ICRRM 2019 – System Reliability, Quality Control, Safety, Maintenance and Management*., pp.179-184 (2020).

Hu, X., Jiang, H., Du, C., "Finite Element Method for Prediction of Rock Breaking Performance of the Tipped Hob With Different Tooth Profiles," *IEEE Access*., Vol.8, pp.50421-50430 (2020).

Hong, W., Cai, W., Wang, S., Tomovic, M.M., "Mechanical wear debris feature, detection, and diagnosis: A review," *Chinese Journal of Aeronautics*., Vol.31, No.5, pp.867-882 (2018).

Jammal, A., Gu, C., Wang, H., Li, R., Song, Y., Rong, Y.K., "An experimental study on high speed helical gears misalignments and dynamic behavior under random loading," *2016 7th International Conference on Mechanical and Aerospace Engineering (ICMAE)*., pp.234-238 (2016).

Kuo, C.-C., Li, D.-Y., Lin, Z.-C., Kang, Z.-F., "Characterizations of Polymer Gears Fabricated by Differential Pressure Vacuum Casting and Fused Deposition Modeling," *Polymers*., Vol.13, pp.4126 (2021).

Kim, S., Kim, C., Jung, S., Kim, Y., "Optimal Design of Novel Pole Piece for Power Density Improvement of Magnetic Gear Using Polynomial Regression Analysis," *IEEE Transactions on Energy Conversion*., Vol.30, No.3, pp.1171-1179 (2015).

Montonen, J., Nerg, J., Polikarpova, M., Pyrhönen, J., "Integration Principles and Thermal Analysis of an Oil-Cooled and -Lubricated Permanent Magnet Motor Planetary Gearbox Drive System," *IEEE Access*., Vol.7, pp.69108-69118 (2019).

Mara, S., Arslan, H., Birgoren, B., "Detection of Gear Wear and Faults in Spur Gear Systems Using Statistical Parameters and Univariate Statistical Process Control Charts." *Arabian Journal for Science and Engineering*., Vol.46, No.12, pp.12221-12234 (2021).

Nguyen, C.D., Prosvirin, A., Kim, JM., "Fault Identification of Multi-level Gear Defects Using Adaptive Noise Control and a Genetic Algorithm," *Intelligent Human Computer Interaction. IHCI 2020. Lecture Notes in Computer Science*., pp.325-335 (2021).

Popovich, A.G., "Determination of the Helical-Gear Geometry Taking Account of Total Teeth Wear," *Russian Engineering Research*., Vol.40, No.12, pp.981-987 (2020).

Sharma, V., Parey, A., "Effect of Lubricant on the Stiffness and Damping Characteristics in a Single-Stage Gearbox: A Theoretical Analysis," *Reliability and Risk Assessment in Engineering*., pp.185-193 (2022).

Trobentar, B., Hriberšek, M., Kulovec, S., Glodež, S., Belšak, A., "Noise Evaluation of S-Polymer Gears," *Polymers*., Vol.14, pp.438 (2022).

Urbas, U., Zorko, D., Vukašinović, N., Černe, B., "Comprehensive Areal Geometric Quality Characterisation of Injection Moulded Thermoplastic Gears," *Polymers*., Vol.14, pp.705 (2022).

Wu, W., Gao, L., Zhang, Y., Li, S., "A recognition method for gearbox wear state based on EEMD and INPP," *2020 3rd International Conference on Electron Device and Mechanical Engineering (ICEDME)*., pp.284-286 (2020).

Wu, T., Wang, G., Li, J., Yan, K., "Structure design and effects of conical gear roller on restraining rabbit ear defects during gear rolling," *The International Journal of Advanced Manufacturing Technology*., Vol.103, No.1, pp.1621-1631 (2019).

Xiao, M., Wang, W., Shen, X., Zhu, Y., Bartos, P., Yiliyasi, Y., "Research on defect detection method of powder metallurgy gear based on machine vision," *Machine Vision and Applications*., Vol.32, No.2, pp. 51 (2021).

Xi, W., Wu, T., Yan, K., Yang, X., Jiang, X., Kwok, N., "Restoration of online video ferrography images for out-of-focus degradations," *EURASIP Journal on Image and Video Processing*., Vol.2018, No.1, pp.31 (2018).

Yan, Y., Shi, X., Zhou, T., Xu, B., Li, C., Lu, Y., Gao, Y., "Machine Learning Virtual SEM Metrology," *2020 International Workshop on Advanced Patterning Solutions (IWAPS)*., pp.1-4 (2020).

Yuan, W., Feng, S., Wang, Z., Guo, Q., Yu, J., "Tribology Analysis of Spherical-Surface Contact Sliding Pairs Under Fluctuating Loads," *Micro and Nanosystems*., Vol.12, pp.23-32 (2020).

Yu, W., Shao, Y., Mechefske, C.K., "The effects of spur gear tooth spatial crack propagation on gear mesh stiffness," *Engineering Failure Analysis*., Vol.54, pp.103-119 (2015).

Yang, L., Wang, L., Yu, W., Shao, Y., "Investigation of tooth crack opening state on time varying meshing stiffness and dynamic response of spur gear pair," *Engineering Failure Analysis*., Vol.121, pp. 105181 (2021).

Yang, Lantao., Wang, Liming., Yu, Wennian., Shao, Yimin., "Investigation of tooth crack opening state on time varying meshing stiffness and dynamic response of spur gear pair," *Engineering Failure Analysis*., Vol.121, pp.105181 (2021).

Yang, Y., Ma, H., Fan, H., Zhang, C., "Design and Test of a Fault Diagnosis System for Planetary Gear Box," *2019 International Conference on Sensing, Diagnostics, Prognostics, and Control (SDPC)*., pp.862-865 (2019).

Zhu, C., Chen, S., Liu, H., Huang, H., Li, G., Ma, F., "Dynamic analysis of the drive train of a wind turbine based upon the measured load spectrum," *Journal of Mechanical Science and Technology*., Vol.28, pp.2033-2040 (2014).

Zhu, C., Chen, S., Song, C., Liu, H., Bai, H., Ma, F., "Dynamic analysis of a megawatt wind turbine drive train," *Journal of Mechanical Science and Technology*., Vol.29, pp.1913 (2015).

Zhang, G.L., Zhang, H.L., Xiao, L., Zou, B.W., "A fractal evaluation method for wear condition of gear based on matter-element model," *Journal of Central South University(Science and Technology)*., Vol.46, No.04, pp.1231-1238 (2015).

線形初始缺陷斜齒輪磨損特征演變研究

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摘要

對於風電、船舶等需要機器在惡劣工況條件下工作的領域而言，齒輪的初始缺陷極大地影響了這些機器的工作性能。本文研究了線形初始缺陷對斜齒輪磨損特征演變的影響，使用激光打標器沿齒寬方向加工出線型初始缺陷，並采用無初始缺陷齒輪進行對照。通過顆粒計數器和鐵譜分析技術對油樣中磨損粒子數量、狀態進行分析，並用掃描電鏡觀測齒面磨損情況。本研究為惡劣工況條件下齒輪磨損狀態評估提供了參考，實驗結果表明：線形初始缺陷改變了輪齒的嚙合狀態，使得齒輪的正常磨損壽命縮短了約 45%，穩定磨損階段的磨損率增加了約 56%，且缺陷齒輪節圓位置發生了大量的點蝕現象以及齒面的塑性流動。此外，潤滑油失效產生的油汙以及軸承損傷產生的硬質顆粒進入嚙合表面及裂紋處，加速了齒輪的磨損進程。