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Contact Fatigue Analysis of Gears

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Abstract: Contact fatigue tests are performed on gears. The pitting evolution of tooth surfaces is monitored by optical microscopy during the test. Wear status of gears is tracked via extracting wear debris from lubricant oil and analyzing debris quantity. After testing, gear teeth are sectioned and inspected under an electron microscope to characterize surface contact features.

Keywords:Contact fatigue; Pitting; Wear debris analysis Scanning electron microscope.

1. INTRODUCTION

The test was carried out on a closed-power-flow contact fatigue test rig. The rig consists of a test gearbox, a slave gearbox, a three-phase AC motor, flexible shafts, rigid shafts, a control panel and a loading coupling. A belt connects the motor and transmits rotational speed to the rigid shaft. To extend the service life of the slave gear pair, its tooth width was increased. The loading coupling deforms the flexible shaft, thereby applying torque to the test gear pair.

2. PITTING OBSERVATION

A digital microscope was used to measure the single-tooth pitting area ratio of the test gears. Ferrography was adopted to separate metallic wear particles from lubricating oil for gear wear prediction. The gears were rotated to locate the tooth with the most severe surface damage for image capture. The tooth surface morphologies at different operating durations are presented in Figure 1.As shown in Figure 1(a), after 18 hours of operation, the gear tooth surfaces underwent initial running-in with slight wear, and tiny pitting pits were observed. Initial pitting inevitably occurs at the early meshing stage due to differences in surface roughness and subsurface non-metallic inclusions. Such pitting generally does not propagate and causes minor damage to gears.Figure 1(b) shows that after 70 hours of operation, individual pitting pits appeared on the tooth surfaces, which were larger than the initial pits yet showed no sign of propagation. This phenomenon is attributed to inherent material defects that reduce the fatigue resistance of the local material around the pits.After 200 hours of operation (Figure 1(c)), the number of pitting pits increased, dominated by micropitting. These tiny pits clustered together and tended to expand further.At 213 hours of operation, the gear failed due to contact fatigue (Figure 1(d)). The scattered pits merged into continuous areas, and a grey line formed on the contact surface, commonly known as a grey spot. Since individual micropits are too small to be identified separately, the aggregation of numerous micropits results in the formation of grey spots.

（a）Tooth surface morphology at 18h

（b）Tooth surface morphology at 70h

（c）Tooth surface morphology at 200h

（d）Tooth surface morphology at 213h

Figure. 1 The tooth surface morphology at different moments observed by microscope

3. GEAR WEAR MONITORING

3.1 Wear Particle Counting

The quantity of wear particles in lubricant serves as a key indicator for evaluating gear wear. In this test, circulating oil injection lubrication was adopted. An oil pump was mounted on the test gearbox to keep the lubricant circulating, so that wear particles were distributed as evenly as possible in the oil. The oil circulation device is shown in Figure 2.

The oil pump remained operational throughout the test to sustain continuous lubricant circulation inside the gearbox. In this way, the collected oil samples could accurately reflect the overall distribution of wear particles and minimize sampling errors.

The collected lubricant samples were tested with a YJS-170 particle counter (see Figure 3) to measure the size and quantity of wear particles. By analyzing samples taken at different time points, the contact condition and wear degree of gears during operation can be determined.

Figure. 2 Gear box lubricating oil circulation device

Figure. 3 Particle counter

The concentration variation of wear particles ranging from 15 μm to 25 μm can best reflect the contact state of tooth surfaces. The corresponding variation curve is shown in Figure 4.

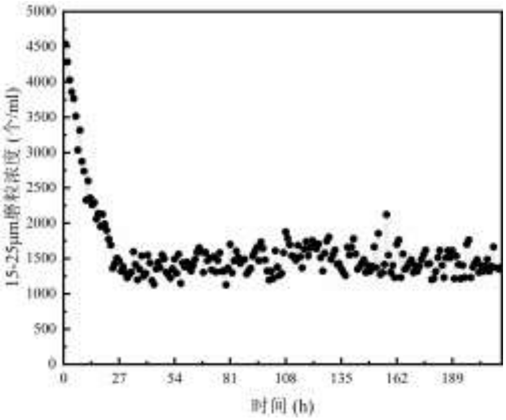


Figure. 4 15μm-25μm abrasive particle number change curve

In the initial operation stage, components go through a running-in period due to machining tolerances and assembly errors, during which the number of wear particles rises rapidly. After running-in, the equipment operates steadily, and the quantity of wear particles in the lubricant fluctuates within a certain range and reaches a dynamic equilibrium. Accordingly, the wear particle concentration remains basically stable under normal operating conditions. In the steady operation phase of the gears, the curve for wear particles sized 15 μm to 25 μm shows no obvious amplitude variation, indicating that no abnormal wear occurs on the gears.

3.2 Ferrography Analysis

Ferrography separates wear particles from lubricant by magnetic attraction, which arranges metallic wear particles in an orderly pattern on ferrograph slides. After slide preparation, a microscope is utilized to analyze the size and distribution rule of wear particles on the slides. The category and dimension of wear particles can reflect variations in wear conditions; accordingly, the wear state of gears can be monitored through particle analysis. The analytical ferrograph adopted in this research is illustrated in Figure 5.

Figure. 5 Analytical ferrospectrometer

After the ferrograph slides are prepared, images of the slides are captured under a metallographic microscope. By comparing the distribution of wear particles on slides collected at different operating stages, the wear evolution of gears over time can be obtained.

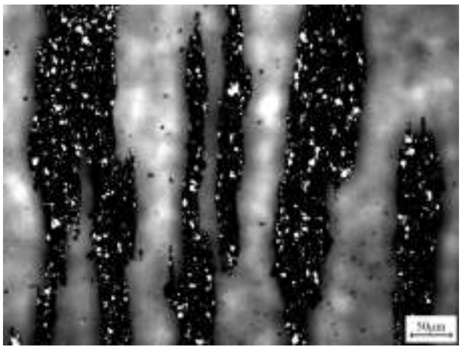


Figure.6 Ferrogram of initial running in stage

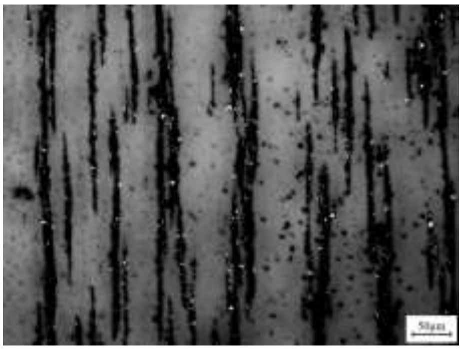
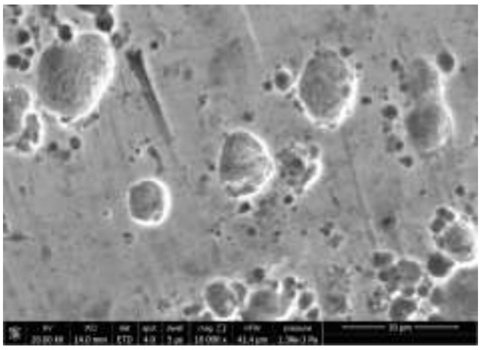


Figure.7 Ferrogram of smooth wear stage

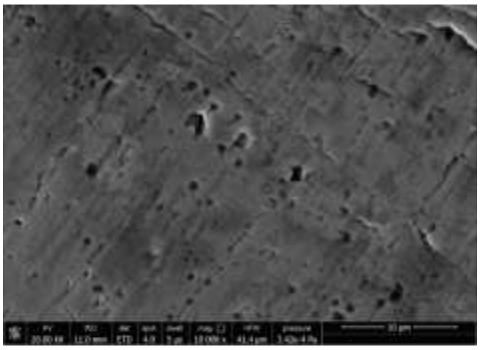
The black strip-shaped substances in the figures are oxidized oil contaminants, while the white particles are wear debris. It can be seen from Figure 6 and Figure 7 that thick chains composed of large and abundant wear particles appear in the initial running-in stage. In the steady wear stage, the particle chains become thinner with fewer wear particles compared with the running-in period.

3.3 Analysis of Gear Fatigue Failure

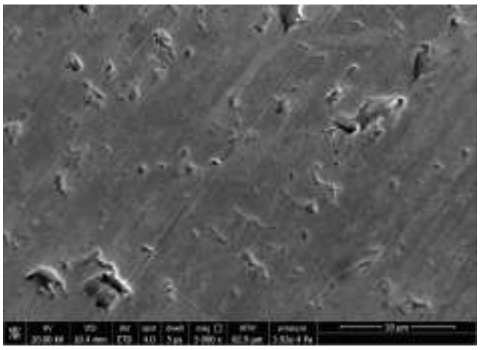
To further investigate the damage and deterioration on tooth surfaces, microscale observation is required. In this paper, a scanning electron microscope (SEM) is used to characterize tooth surface morphologies and analyze the contact failure behavior of gears.The SEM micrographs of gear tooth surface morphology are presented in Figure 8.



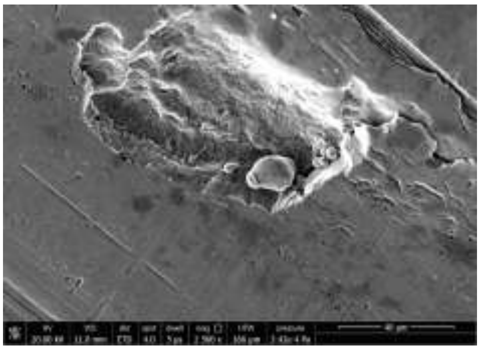
(a) Tooth No.1



(b) Tooth No. 2



(c) Tooth No. 3



(d) Tooth No. 4

Figure. 8 Failure gear tooth surface topography

Figure 8(a) shows the tooth surface morphology at the pitch line with a magnification of 10,000 times. Most pitting pits are semicircular with a diameter of approximately 5 μm, indicating contact fatigue failure induced by micropitting. Figure 8(b) presents the surface morphology of Tooth No. 2. Tiny micropits interconnect to form patchy pockmarks, and cracks emerge between adjacent pits on the contact surface. If operation continues, these cracks propagate both longitudinally and in depth. Once they reach a critical size and intersect with other cracks, large cavities form, and micropitting gradually evolves into macropitting. Figure 8(c) displays the surface morphology of Tooth No. 3 at 5,000× magnification, featuring pitting pits of varying sizes. Judging from the pit morphology, such cavities are presumed to be generated by wear debris trapped within tooth surface contact interfaces. Figure 8(d) illustrates Tooth No. 4 magnified 2,500 times, where relatively large pitting pits are visible. These pits increase surface roughness and trigger severe abrasive wear around their peripheries, further intensifying vibration and noise during transmission.Observation of tooth surface morphologies reveals that the dominant damage form is micropitting. Benefiting from continuous advancements in gear material quality, machining procedures, heat treatment and surface modification technologies, subsurface-initiated failures such as conventional macropitting are far less prominent than in the past. Consequently, micropitting has become one of the primary bottlenecks restricting the service life and reliability of gears.

4. CONCLUSION

This chapter conducts contact fatigue tests on gears. During the test, the pitting behavior of gear tooth surfaces is observed via a microscope. Lubricant samples are extracted during gear operation. A particle counter is adopted to analyze the wear particle quantity in lubricant, and ferrography technology is used to characterize wear particle morphology, so as to evaluate the gear wear state. The failed gears are observed by a scanning electron microscope (SEM) for tooth surface morphology. Numerous tiny pitting pits are detected on the tooth surface, proving that gear failure is contact fatigue failure caused by micropitting..

5. REFERENCES

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