Analysis and prediction of gear fatigue life

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Abstract. The fatigue test data of gear material is used to get the S-N curve of gear material, the calculation the fatigue life of gear is done through finite element analysis, this way of the fatigue life of gear analysis provide a way of thinking for the fatigue life of gear research method.

Key words: Gear fatigue life; S-N curve; Fracture analysis.

1. Introduction
From the point of view of fatigue science, fatigue research mainly focuses on the fatigue strength and fatigue life of materials or structures under repeated loads. For the fatigue life problem of gear structure, the most common method is to adopt the actual fatigue life test of gear. Although this method can reflect the actual fatigue life of gear, it is often time-consuming and inefficient. Therefore, it is necessary to use modern analysis technology combined with rapid test technology for rapid and efficient gear fatigue life prediction, improve the efficiency of gear design and analysis, reduce the cost of gear test.

2. Basic theory of fatigue analysis
In order to estimate the fatigue life of materials or parts, it is necessary to obtain the corresponding parameters by certain means and feasible methods. The most common method is to use the S-N curve of basic fatigue strength characteristics of materials. Linear fatigue damage theory, which contains Miner theory and modified Miner theory are mainly used in engineering. Miner theory is most widely used when load order is not considered. Miner theory, also known as linear cumulative damage theory, N is assumed to be the fatigue life under the current load level $\sigma$. Then, the damage of parts within a cycle is:

$$ D = 1 / N $$  \hspace{1cm} (1) $$

In the case of constant amplitude load $n$, the above formula becomes

$$ D = n / N $$  \hspace{1cm} (2) $$
The variable amplitude load is equivalent to the linear superposition of different equal amplitude loads, if the fatigue life under the corresponding load level \( \sigma_i \) is \( N_i \), then the corresponding damage is:

\[
D = \sum_{i=1}^{n} \frac{n_i}{N_i}
\]  

(3)

when \( D = 1 \) there is the critical fatigue damage, For the case of constant amplitude load \( n = N \).

3. Fatigue test method and theory

In order to conduct more accurate fatigue analysis of gears, corresponding fatigue tests are needed to obtain fatigue strength of materials and S-N curve of materials, so as to provide data support for fatigue life analysis of gears. In order to reproduce the fatigue performance tests carried out in different materials, batches and different test sites, standard parts and standard test procedures are required.

3.1. Fatigue strength test of gear materials

Based on the basic theory of fatigue test and the relative standard, the fatigue performance test of gear material containing standard specimen is adopted to provide data support for the calculation of fatigue life of gear. At present, most of the automobile gears are made of alloy steel. In order to expand the gear material warehouse and explore the application of new materials with excellent performance in automobile gears, high-strength steel is selected as the research object. The design reference of the specimen is in accordance with the standard [1], and the axial loading smooth specimen recommended by the national standard is adopted. The standard recommends two kinds of cross section specimens. Rectangular cross section specimens are used. The static test equipment is a hydraulic universal test machine, and the fatigue test equipment is a 20T high-frequency fatigue test machine with a frequency of 80-120Hz, model jxg-200.

Before the axial tensile fatigue test, specimens J1 and J2 were selected for static tensile test to obtain the yield limit and tensile limit of the material. The linearity of the two specimens is better within the load range of 80KN and less. The yield strength of the two specimens is 698.3mpa and 743.13mpa, and the tensile strength is 812.82MPa and 800MPa, respectively. The test is completed when the specimens are disconnected after yielding. The yield strength and tensile strength of the two specimens are not different, and the data consistency is good. The fatigue test results of a group of 16 standard specimens are shown in Table 1.

| Specimen number | Biggest stress(MPa) | Static load(KN) | Dynamic load(KN) | Number of cycle(time) | Results of test | Damage location |
|-----------------|---------------------|-----------------|-------------------|----------------------|----------------|----------------|
| 1               | 400                 | 34.68           | 28.37             | 1.00E+07             | not damage     |                |
| 2               | 440                 | 35.96           | 29.43             | 1.00E+07             | not damage     |                |
| 3               | 480                 | 39.74           | 32.52             | 1.596E+06            | crack          | U middle       |
| 4               | 460                 | 40.27           | 32.95             | 6.391E+06            | crack          | Arc itd        |
| 5               | 450                 | 36.72           | 30.04             | 1.00E+07             | not damage     | Arc itd        |
| 6               | 460                 | 39.98           | 32.71             | 6.977E+05            | crack          | Arc itd        |
| 7               | 460                 | 42.30           | 34.61             | 1.00E+07             | not damage     |                |
| 8               | 470                 | 43.28           | 35.41             | 1.00E+07             | not damage     |                |
| 9               | 500                 | 45.82           | 37.49             | 1.00E+07             | not damage     |                |
| 10              | 540                 | 46.96           | 38.42             | 1.368E+06            | disconnect     | Middle         |
| 11              | 520                 | 44.37           | 36.31             | 1.00E+07             | not damage     |                |
| 12              | 540                 | 44.60           | 36.49             | 1.00E+07             | not damage     |                |
| 13              | 560                 | 48.76           | 39.90             | 5.375E+05            | crack          | Arc itd        |
| 14              | 540                 | 45.98           | 37.62             | 3.477E+05            | crack          | Arc itd        |
| 15              | 520                 | 45.46           | 37.19             | 9.371E+05            | crack          | Middle         |
| 16              | 520                 | 42.72           | 34.96             | 1.00E+07             | not damage     |                |
3.2. Fatigue fracture analysis of specimens

The fracture of fatigue failure specimen has obvious characteristics both macroscopically and microscopically. By analyzing the fracture of fatigue failure, it is of great significance to understand the process of fatigue fracture, study the mechanism of fatigue problems and explore the causes of fatigue accidents. The fracture state after the test was analyzed, and the appropriate parent was selected for analysis. No. 10 specimen was selected as the parent for analysis. After grinding, the surface quality of this specimen was better. After the disconnection of the specimen, corresponding protection was given to the fracture, and it was found that the fracture protection was better before the linear cutting. The fracture condition is also good after linear cutting. Macroscopic observation shows that the fracture presents two obvious regions, namely smooth zone and rough zone. Fracture is a typical fatigue fracture, and the fatigue source area is in the smooth zone of fracture. According to the amplification and scanning of the morphologies of each region of the fracture location, the fracture was analyzed. Fig. 1 shows the morphology of the corresponding section numbered 33 at different magnification. The smooth area in the middle of Fig. 1 is the fatigue source area. Fatigue crack source area is the first place, in the process of fatigue test, due to the sustained load cyclic stress, the fatigue area frequently, therefore presents a smooth section, on both sides of the coarse grain of uneven topography is the expansion of the fatigue area, at this time, due to local recurrence can't bear load, present a tear, so the surface is very rough.

![Fig. 1 Subsurface morphology of fatigue fracture under1000 μm](image)

4. Gear fatigue life analysis

4.1. S-N curve of gear material

According to the test results of gear material, the S-N curve of gear material is obtained by processing the test results. Since the test results are discrete data points, a certain method of data fitting is needed. The S-N curve of the material is fitted by the usual power function formula. The basic formula for a power function is

\[ \sigma'^{m} N = C \]  

(4)

take the logarithm and get the formula

\[ m \log \sigma + \log N = \log C \]  

(5)

Where, \( m \) and \( C \) is the material constant, then the corresponding \( \log \sigma \) and \( \log N \) equation is obtained. The number of cycles under different stress levels can be obtained by experimental results, and then the
material constant can be obtained. By using the least square method for formula fitting, the equation corresponding to the S-N curve of the material can be obtained as follows:

\[
\lg N = 39.28 - 12.20 \lg \sigma
\]

4.2. Calculation of gear fatigue life

Every time the gear rotates in the working process, a single gear tooth of the gear is loaded once. In the static analysis of gear, the main focus is on the load capacity of gear under the action of the maximum working load, mainly for a specific moment in a specific position of the gear case for detailed analysis. Under the action of load, the tooth root of the gear will produce bending deformation. The bending stress on the compression side and the tension side shows a certain rule, and the bending stress value at the root point of a single tooth is the maximum. Therefore, in the process of fatigue calculation, single tooth root is selected as the fatigue life calculation condition. The load of a single gear tooth is simplified to a sine curve to simulate the cyclic loading. The fatigue life is calculated according to the stress of the gear tooth and the cyclic loading curve, and the design life is \(1 \times 10^7\), the modulus of 2.87, the pressure Angle of 20°, number of teeth of 19, gear width of 16 mm, center distance of 54.574mm, the load of 52.25 N · m is applied for the finite element analysis of involute gears’ fatigue life analysis as an example. The fatigue life cloud diagram of gear is shown in Fig. 2. At the moment of single tooth roasting, the minimum contact fatigue life of the gear is 107.9 times, the minimum bending life is 1012.9 times, and the minimum bending life occurs at the center of the tooth root arc on the pressed side of the gear. The fatigue safety coefficient distribution of gear is shown in Fig. 3. As can be seen from the figure, the minimum fatigue safety coefficient of the gear in the design life is 1, which appears in the tooth section of the load position on the tooth surface, and the gear has enough resistance to fatigue.

![Fig. 2 cloud diagram of gear fatigue life](image-url)
Fig. 3 distribution of fatigue safety coefficient of gear

5. Conclusion
In order to reproduce the fatigue performance tests carried out in different materials, batches and different test sites, standard parts and standard test procedures are required. Fatigue life analysis of gear according to the fatigue life theory, the fatigue test of gear material with standard parts is carried out to obtain the fatigue performance data of the material. Using the experimental data and fatigue analysis theory, using the finite element analysis method, the bending fatigue life of gear is obtained. The proposed method is useful to analyze and predict the fatigue life of gears quickly.

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