The Study on Basic Fatigue Properties of the New Axles Steel and Axle Fatigue Assessment

Qingfeng Liu¹, Yawen Lyu², Liang Yan¹ and Hua Zou³

¹Unit No. 92228, Beijing 100072, China, Email: liuqingfeng72@163.com
²Beijing Rosedale Filter Systems Company
³Beijing Jiaotong University

Abstract. With the development of the high speed railway construction, we pose a higher demand for the performance of EMU. This subject is designed to get the information about the new axle materials’ S-N curve by testing the fatigue property of axle materials. With the help of finite element simulation, finite element model of wheel pair could be built. Through the method of numerical simulation, we could know the stress distributing when wheel pair are stressed, and evaluate the intensity of axles.

1. Introduction
The axle is a key part of high-speed train vehicles to bear dynamic load, which is in a complex state of force. It mainly bears bending load, torsional load or composite bending and torsional load, and is subject to impact. Therefore, the axle can be broken due to bending, torsion or tensile stress during work, and fatigue fracture is a common form of axle fracture. Therefore, for axle steel, it is mainly to ensure its good strength, especially the bending and torsional composite fatigue strength and toughness. In order to prevent the rapid wear of the axle journal, it should also have a enough surface hardness.

In recent years, the development of computer hardware and software technology and the progress of fatigue damage theory research have provided new methods, for the theoretical calculation of fatigue life. Among them, the numerical simulation calculation technology based on the finite element method (FEM) is widely used in product fatigue life assessment and quantitative life design. This not only improves the accuracy and reliability of theoretical calculations, but also simplifies the calculation of some complex problems. It also plays a very important role in saving development time and cost in the design of new products.

This paper used the four-point bending fatigue test method to evaluate the fatigue limit of the axle material, and analyzed the fatigue strength of the axle material by establishing a finite element model of the axle.

2. Test Materials and Methods

2.1. Selection and Design of Fatigue Test Samples for Axle Materials
According to JB/T9374-1999 “Specifications for the rotary bending fatigue testing machines”, this test used PQQ-60 pure bending rotating fatigue testing machine. According to the characteristics of the test rotary bending fatigue testing machine fixture, the shape and size of the sample material were designed.

The four-point bending fatigue test method was adopted, and the test piece was designed and manufactured in strict accordance with the standard "Metal Material-Fatigue Test-Rotation Bending
Method” to ensure that the sample brake in the middle part, obtained valid data, and improved the test success rate[1,2].

2.2. Analysis of Loading Condition of Fatigue Test
As shown in Fig. 1, several small samples were cut and processed on the same material rotating axle test piece for the test of material fatigue performance. Clamped the samples to the fatigue testing machine, and avoided the stress of the sample part other than the applied force during installation. Ensured that the coaxiality required for the test was met before applying the force. The clamped sample and its stress state were shown in Fig. 2.

Four-point simply supported beam sample stress: 
\[ S = \frac{M}{W} = \frac{32PL}{\pi d^3} \]

Where: M is the bending moment received; W is the flexural section modulus; P is the vertical load; L is the beam length; d is the section diameter. Then the weight force is 
\[ P = \frac{\pi d^3 S}{32L} \]

In this test, d=8mm, L=60mm, \( S = 0.47 \sigma_b \approx 376MPa \). The calculated stress was the maximum bending stress on the outer surface of the middle section of the sample.

3. Test Results and Data Processing
3.1. Test Method and Data of Single Point Method
Generally, a fatigue limit value is estimated based on the tensile strength of the material, and then the fatigue test is started at a stress level that is a certain percentage higher than the estimated value. Gradually reduce the stress and carry out the fatigue test of the next sample until one sample is tested until the test base does not break. The average value of the stress between the unbroken sample and the adjacent stress level is its fatigue limit.

Table 1. The test data by the single point method

| NO. | N (10^4) | S (MPa) | N (10^4) |
|-----|----------|---------|----------|
| 1   | 357      | 426.14  | 1.9      |
| 2   | 337      | 402.26  | 5.9      |
| 3   | 287      | 342.58  | 1042.8   |
| 4   | 312      | 372.42  | 46.3     |
| 5   | 297      | 354.52  | 145.3    |
| 6   | 292      | 348.55  | 52.2     |
The rough fatigue limit value obtained by the above operation was $\sigma_{-1} = 344.97$ MPa.

3.2. Test Method and Data Processing of Lifting Method

Due to the dispersion of fatigue performance, the fatigue limit determined by the conventional method is inaccurate. In order to obtain a more accurate fatigue limit, the lifting method must be used. The large sample lift method proposed abroad requires the use of more samples, and the number of samples should generally not be less than 30. In order to reduce the number of samples, Professor Gao Zhentong proposed a small sample lifting method that can save samples based on the theory of "pairing". At present, this method is mostly used in China to determine the fatigue limit [3].

The rough fatigue limit value obtained by the single-point method was $\sigma_{-1} = 344.97$ MPa. Taken stress difference as: $\Delta \sigma = (4\% \sim 6\%) \sigma_{-1} = (13.799 - 20.698)$ MPa.

Therefore, the stress value of each level was obtained as $\sigma_{-1} \pm \Delta \sigma$, $\sigma_{-1} \pm 2\Delta \sigma$; but since the calculated stress value in the test might not be guaranteed by the weight, the data was adjusted according to the actual situation of the fatigue test device and listed in Tab. 2.

**Table 2.** The stress level after adjustment by the lifting method

| Stress level | Expression | Weight (N) | Stress (MPa) |
|--------------|------------|------------|--------------|
| 1            | $\sigma_{-1} - \Delta \sigma$ | 277        | 330.64       |
| 2            | $\sigma_{-1}$     | 287        | 342.58       |
| 3            | $\sigma_{-1} + \Delta \sigma$ | 297        | 354.52       |

Thus, the small samples lifting method was tested according to the weight determined in Tab. 2.

**Table 3.** The test data by the lifting method

| No. | P (N) | S (MPa) | N        |
|-----|-------|---------|----------|
| 1   | 297   | 354.52  | 1407585  |
| 2   | 287   | 342.58  | 1479190  |
| 3   | 277   | 330.64  | 11592985 |
| 4   | 287   | 342.58  | 399476   |
| 5   | 277   | 330.64  | 11415871 |
| 6   | 287   | 342.58  | 13574891 |
| 7   | 287   | 342.58  | 660224   |
| 8   | 277   | 330.64  | 1013125  |
| 9   | 267   | 318.71  | 16764813 |

Matched the results according to the lifting method:

**Table 4.** Test data matching

$S_i \sim S_{i+1}$ MPa, $S_{ni} = \frac{1}{2}(S_i + S_{i+1})$ n

| $S_i$ | $S_{ni}$ | n |
|-------|----------|---|
| 342.6 | 330.6    | 2 |
| 342.6 | 354.5    | 1 |
| 330.6 | 318.7    | 1 |

According to the test results, the relevant values of the fatigue limit were obtained:

Sample weighted average: $S_{50} = \frac{1}{n} \sum S_i n_i = 336.6$ MPa

Sample standard deviation: $S = \sqrt{\frac{\sum n_i (S_i - S_{50})^2}{n-1}} = 8.44$ MPa
Coefficient of variation: $\frac{\hat{S}}{S_{50}} = 0.0251$

As long as the coefficient of variation was less than 0.15, the data dispersion met the test requirements. So the data was good.

3.3. S-N Curve Drawing

Statistics and draw corresponding curves of data:

1) Single-point method data processing. According to the test data in Tab. 1, plotted the S-N curve with the stress of the sample as the ordinate and the logarithm of the number of cycles as the abscissa.

2) Lifting method data processing. According to the test data in Tab 4, took the stress of the sample as the ordinate and the logarithm of the number of cycles as the abscissa, and drew the curve.

Figure 3. The S-N curve by the single point method

Figure 4. The curve by the lifting method

In the Fig.4, ○ means the sample is not broken, × means the sample is broken.

In the Fig. 4, the point on the corresponding line when the X coordinate is 1E7 is the fatigue limit of the material. The data is fitted by Origin, and the stress value at this point is 336.6MPa.

4. Static Strength Analysis of Axle Material

4.1. Establishment of Finite Element Model of Axle

An 8-node hexahedral element (SOLID45 element) was used to mesh the wheel and axle models, and a finite element model was obtained as Fig. 5.
4.2. Load Condition

The calculated load conditions and strength evaluation method were determined according to the EN13103 regulations[4]. The relevant parameters of the axle and the calculation results of each force value were obtained by calculation in Tab. 5, and the loaded the axle.

Table 5. Basic data and the result of the stress

| $m_1$ | $h_1$ | $b$ | $s$ | $R$ | $y_1$ | $F_1$ | $P_1$ | $P_2$ | $Y_1$ | $Y_2$ | $Q_1$ | $Q_2$ |
|-------|-------|-----|-----|-----|-------|-------|-------|-------|-------|-------|-------|-------|
| kg    | mm    | mm  | mm  | mm  | mm    | kN    | kN    | kN    | kN    | kN    | kN    | kN    |
| 14205 | 1425  | 800 | 531.5 | 425.5 | 291.5 | 7.4 | 105.6 | 68.4 | 41.8 | 20.9 | 118.0 | 48.6 |

4.3. Calculation Results

Under this operating condition, the maximum axial stress on the axle was 76.989 MPa, which occurred in the transition zone between the wheel and the axle.

5. Determination of Fatigue Limit of Axle

The S-N curve and fatigue limit of the material can only represent the fatigue performance of the standard smooth sample. The size, shape and surface condition of the actual parts are various, which is very different from the standard sample. So we have to determine the fatigue limit of the actual axle.

Use the corresponding relationship between the test sample and the actual component according to the formula: $\sigma_{-1} = \frac{\varepsilon \beta}{k} \sigma_{-1s}$

Where: $\varepsilon$ is the size factor; $\beta$ is the surface factor; $k$ is the theoretical stress concentration factor; and $\sigma_{-1s}$ is the fatigue limit of the standard smooth sample.
By referring to the literature[5], and combining the dimensions and manufacturing processes of the axle materials, we can obtain the corresponding coefficients: $\varepsilon = 0.7$, $\beta = 0.9$, $k = 2$. And because the fatigue limit is the result of a normal distribution, we should consider the case where the fatigue limit is the smallest. According to the $3\sigma$ rule, $\sigma_{-\varepsilon} = \mu - 3\sigma = 287.41MPa$.

According to the determination of these parameters, we had obtained $\sigma_{-\varepsilon} = 90.53MPa \geq 72.414MPa$ through experiments. It was concluded that the new axle steel could meet the normal working needs. The material ratio for the axle could be used.

6. Conclusion
This subject completed the fatigue test of the axle material and statistically sorts the data, and drew the S-N curve of the axle material. Then, according to EN13103, the finite element simulation calculation of the axle was completed, and the fatigue limit of the axle was determined.

Due to various reasons, there are still many deficiencies in the research work, from which the following points of experience are obtained:

(1) When drawing the SN curve of the material using the lifting method, the stress level should be as much as possible if the sample material allows, so as to obtain a variety of test data under the same stress level. The impact of the individual test sample differences on the test is minimized, and a more accurate fatigue life curve is obtained.

(2) During the test, the sample installation process should be rigorous and careful. Four-point force is used to ensure that the location of the sample is basically the same. Therefore, the influence of artificial components in the test device is minimized.

(3) In the finite element calculation of the axle, we found that the location of the maximum axial stress is the transition area between the wheel and the axle, so we should consider the junction of the axle and the wheel in future research. The axle and wheel studied this time are integrated, and in reality, most wheels have an interference fit between the wheel and the axle. The center of the wheel and the hub in addition to the load, and the static stress caused by the interference fit is also larger. The research shows that the stress state of the wheel and axle fitting part has an important influence on the fatigue strength of the axle[6]. Therefore, the research on the macro-contact stress state and safety assessment of the wheel-axle matching parts will help to guide the formulation of wheelset manufacturing standards, the design of high-speed and heavy-loaded wheelsets, and the improvement of processing technology to improve the fatigue resistance of wheelsets.

7. References
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